Deciphering the Universe:

Cryogenic detectors for neutrino and dark matter searches

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University of Milano-Bicocca
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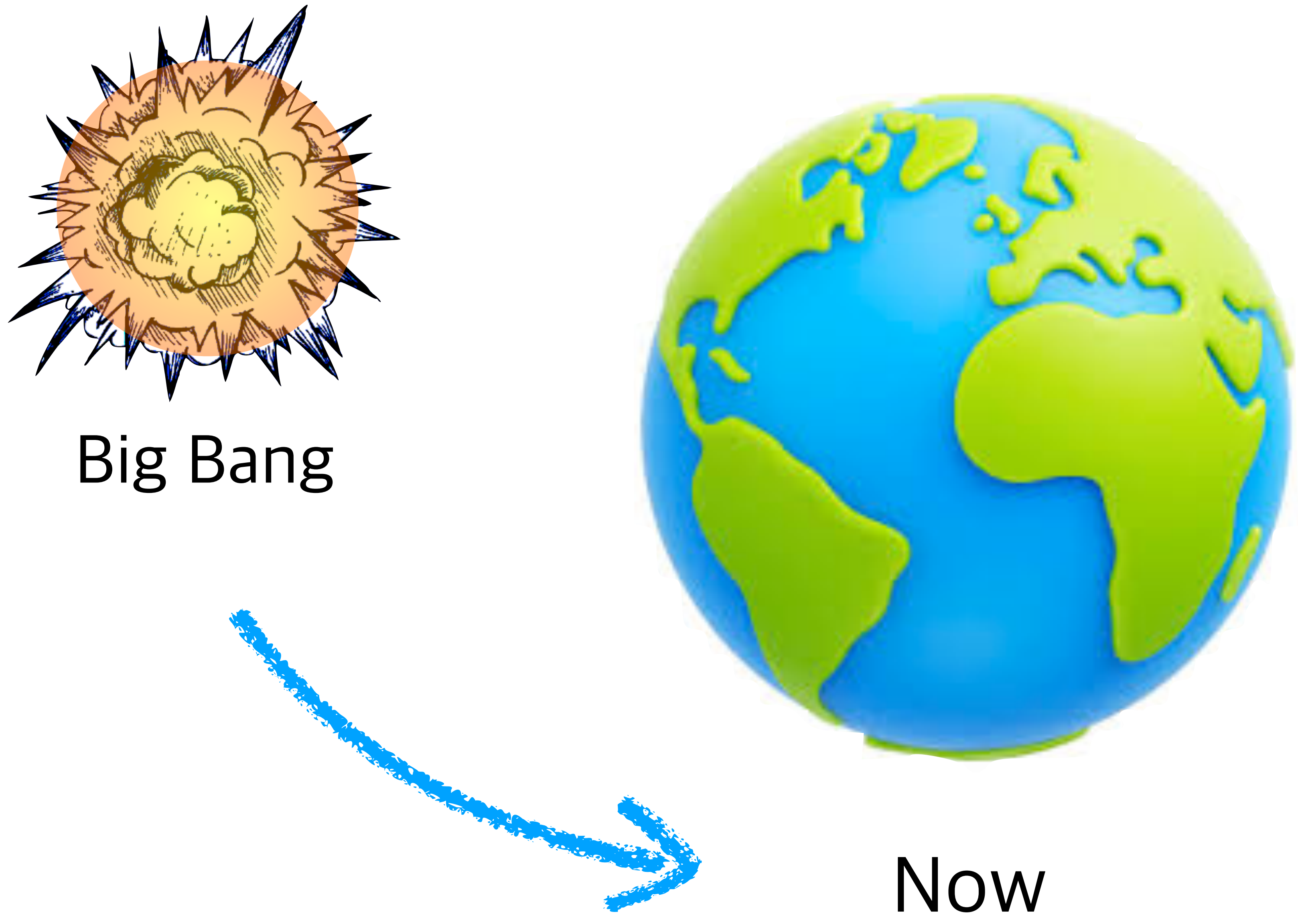
Max Planck Institute for Physics - Garching - May 21st, 2024

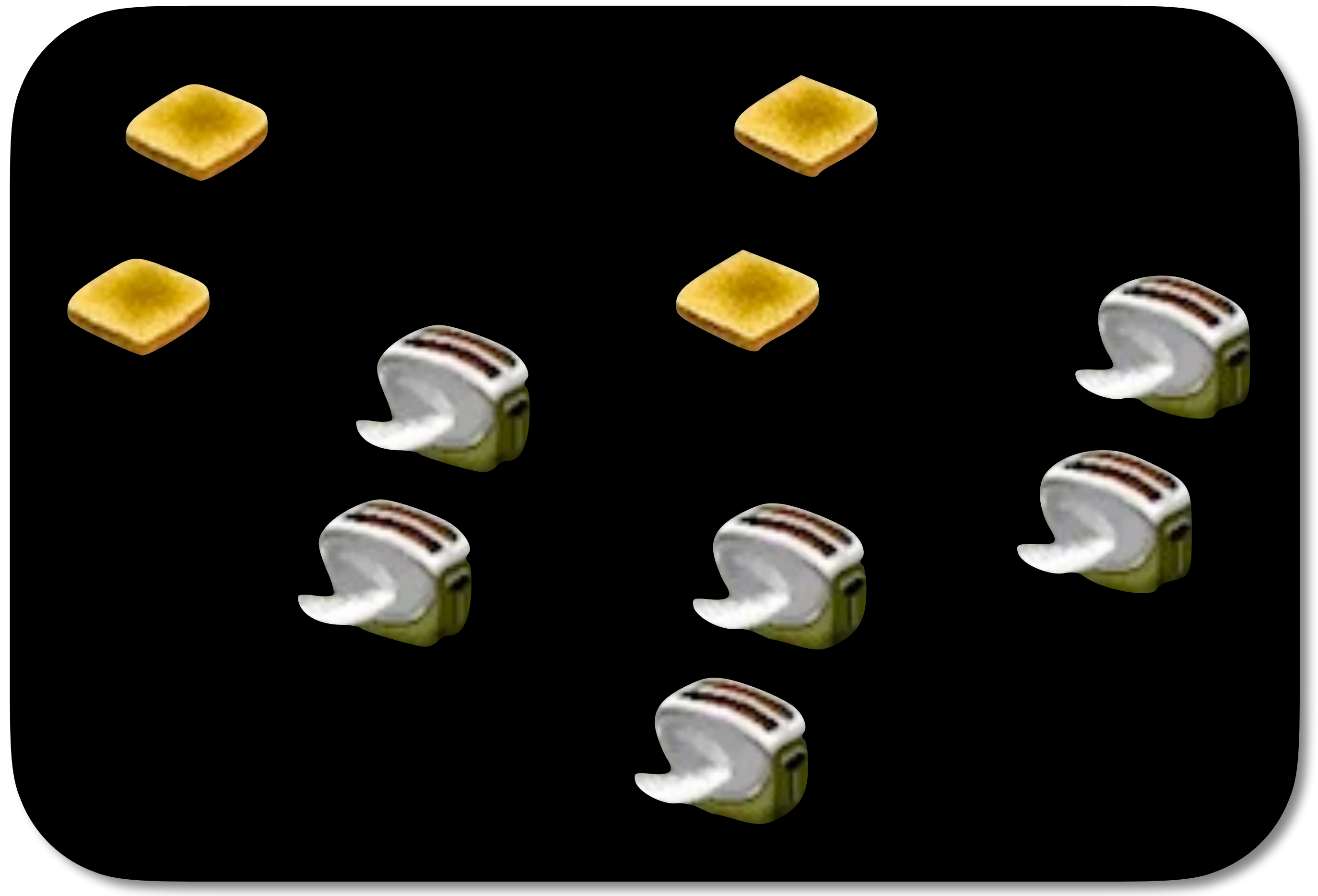
Motivation

What is matter ?



Matter-antimatter asymmetry
How matter is created ?

Neutrinos & Dark Matter



most abundant particles
as probes

Sensitive technology

Cryogenic detectors

Open questions

What is matter ?

Neutrino properties

Astroparticle observatory

Dark Matter searches

3

Open questions

What is matter ?

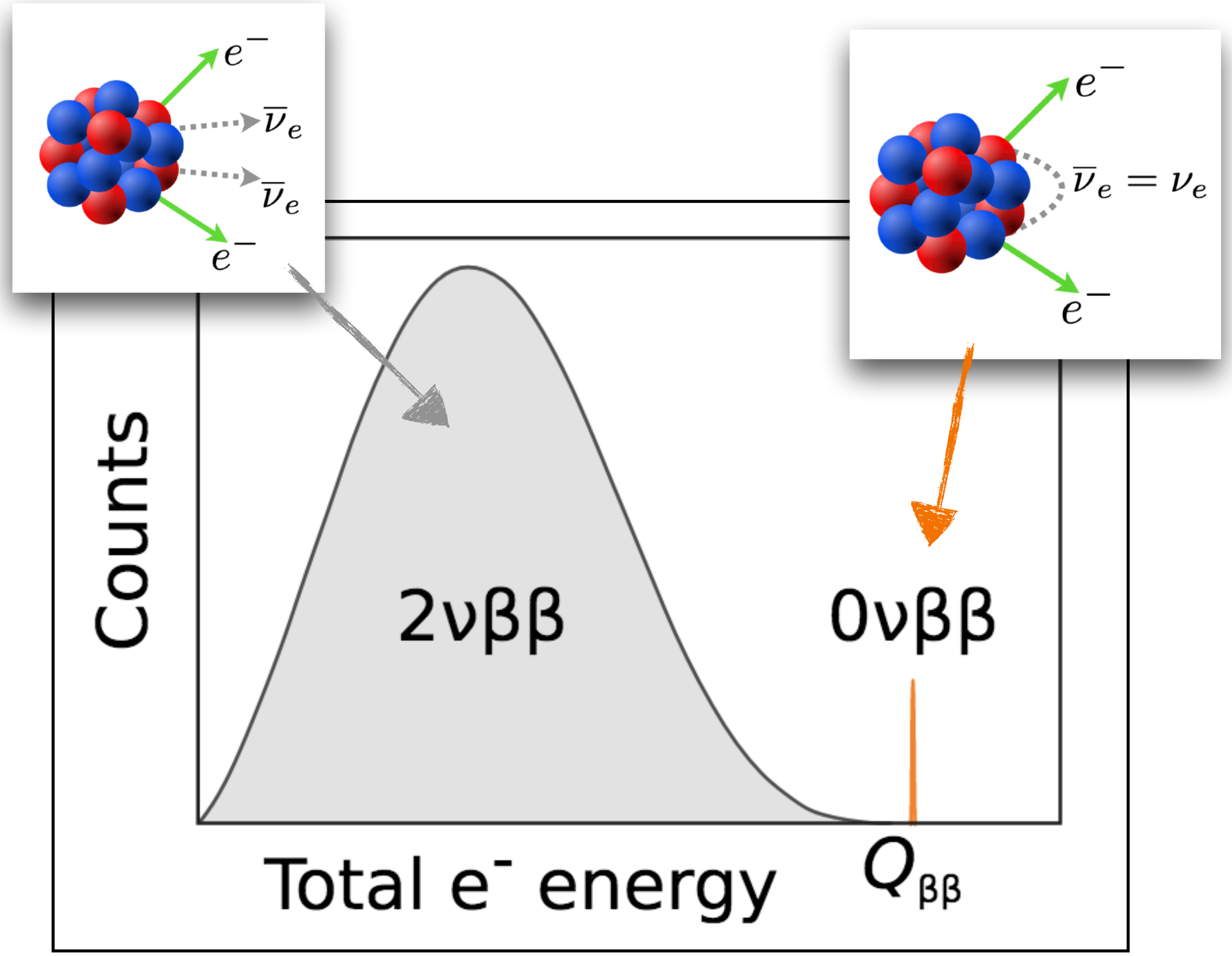
Neutrino properties

Astroparticle observatory

Dark Matter searches

How matter is created?

Neutrinoless double-beta decay



Shed light on matter-antimatter asymmetry

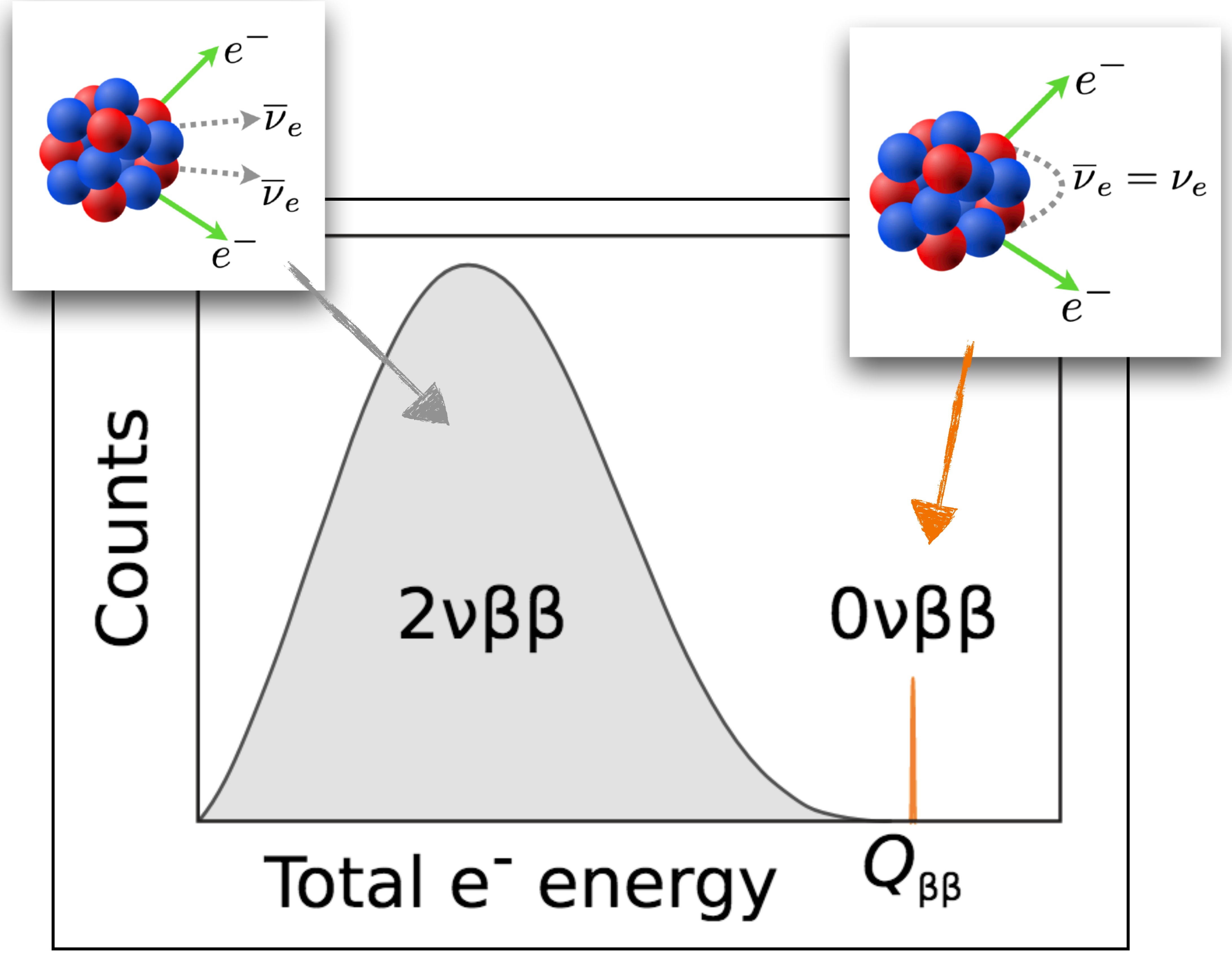
Neutrinos are Majorana particles

Half-life measures neutrino mass:

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q,Z) \cdot |M^{0\nu}|^2 \cdot \boldsymbol{m_{\beta\beta}^2}$$

How matter is created?

Neutrinoless double-beta decay



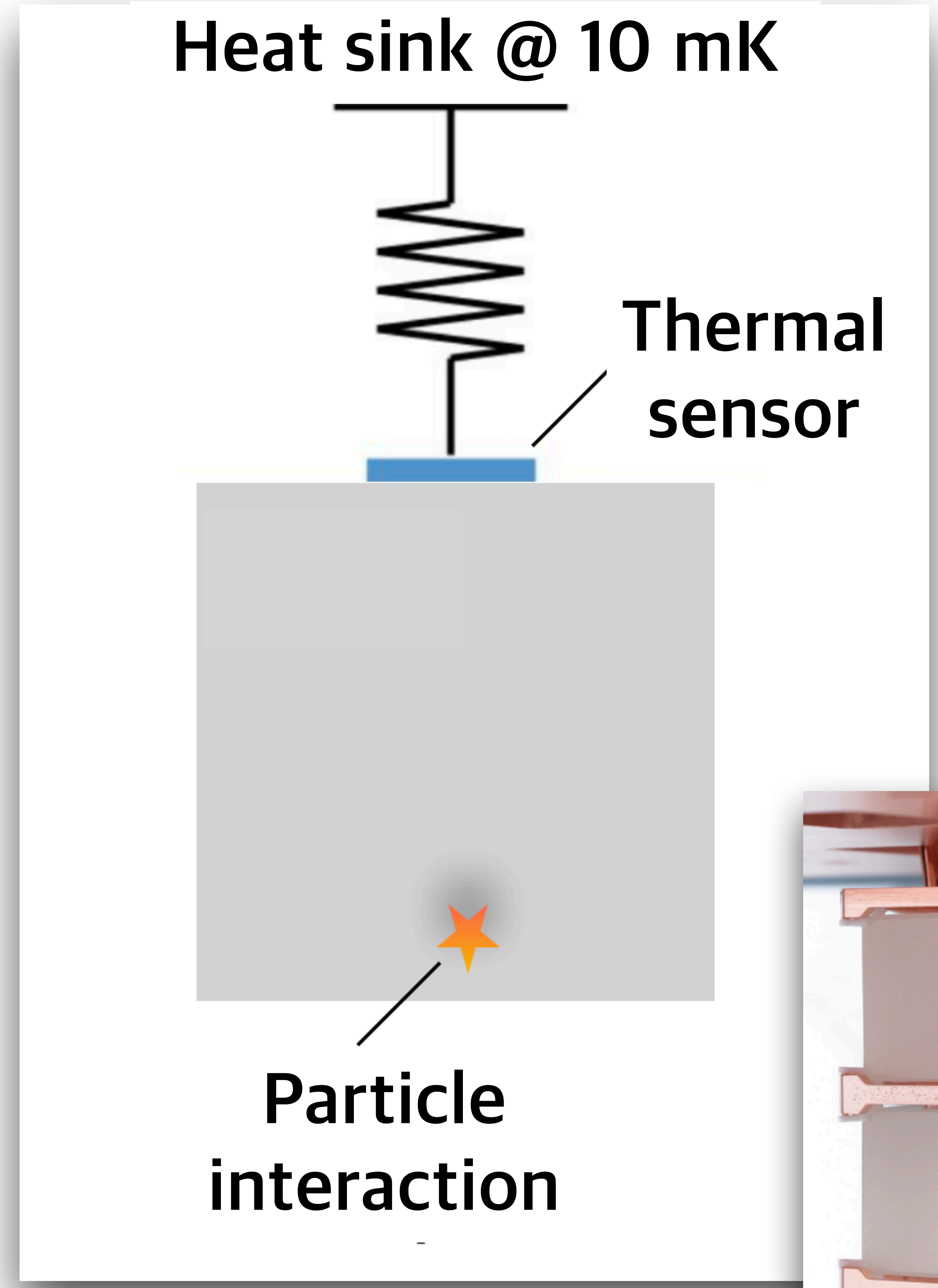
Rarest decay $\tau > 10^{26}$ y

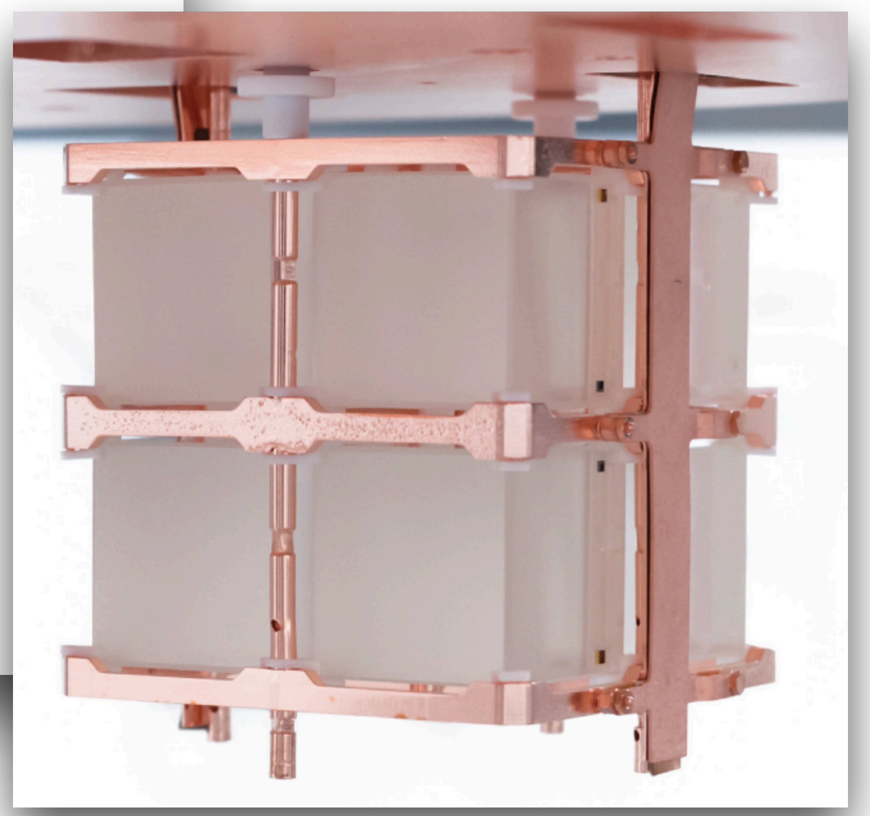
Experimental parameters:

- Large exposure (ton×y)
- Ultra-low-background (1 c/ton/y/RoI)
- Excellent energy resolution (~0.1% @ RoI)

What is a cryogenic detector ?

Low-T calorimeter



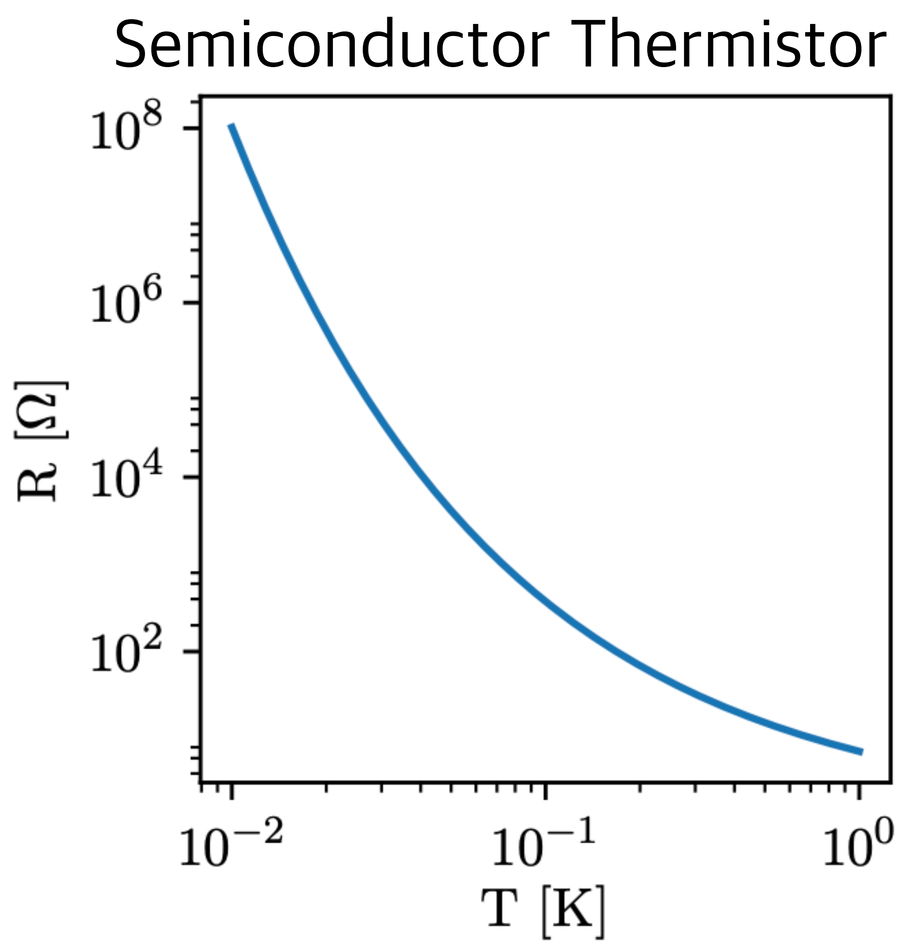


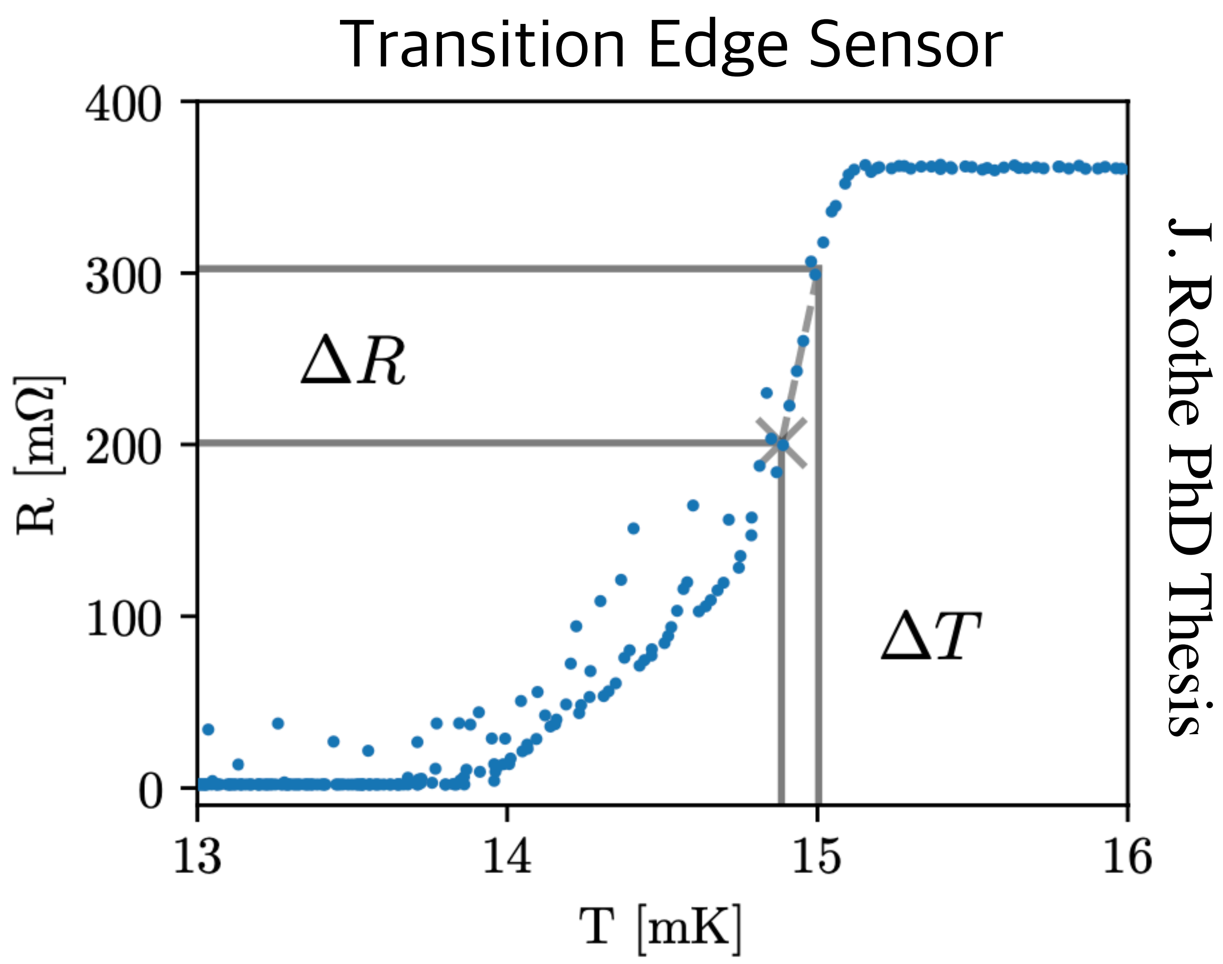
C ~ O(pJ/K) ~ O(keV/μK)

A highly sensitive calorimeter operated @ 10 mK

Energy deposits are measured as temperature variations of the absorber.

Thermistors are a key technology





CUORE experiment

1 m^3 detector @ 10 mK

World's largest cryogenic detector

@ underground of LNGS (3600 m w.e.)

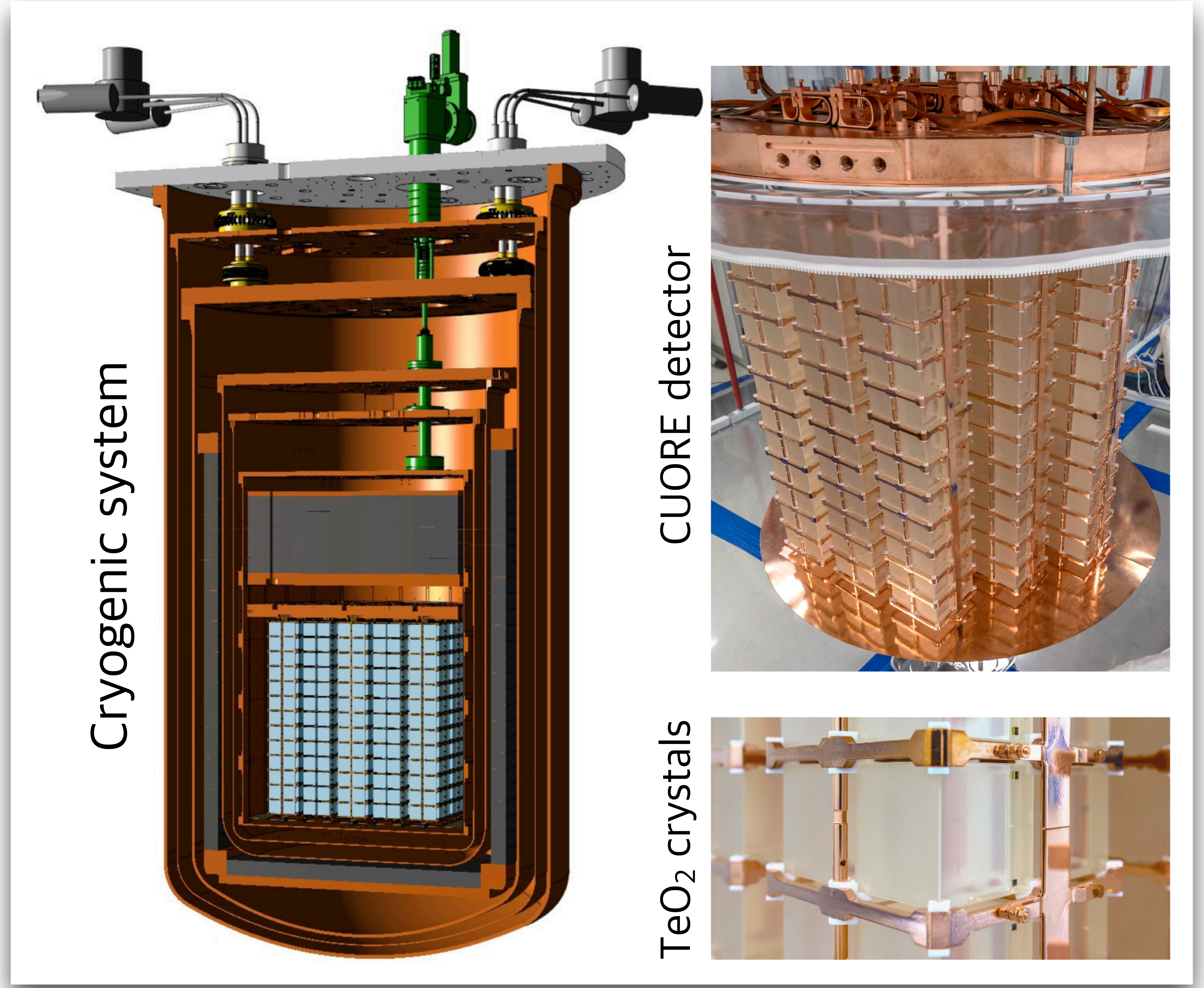
International collaboration (100+ members)

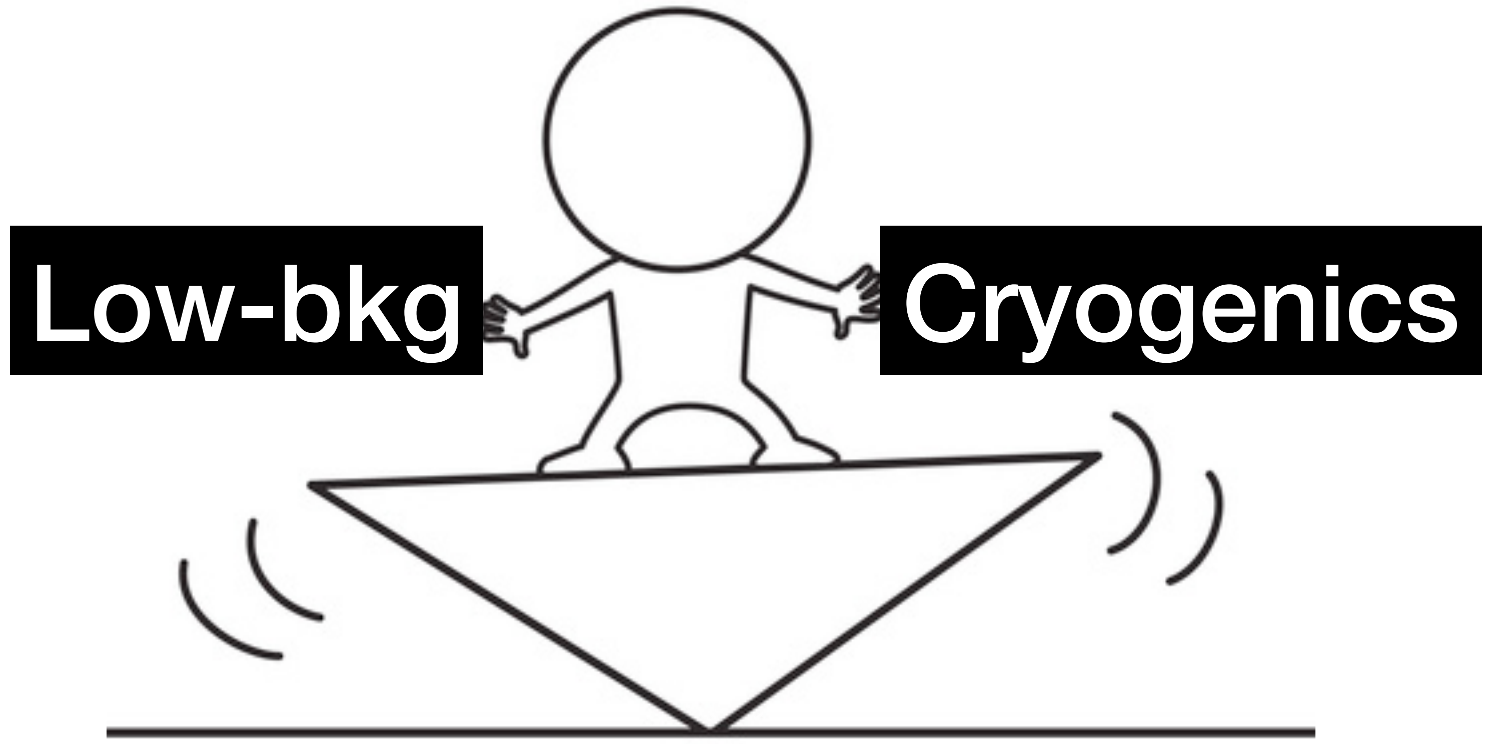
Detector:

- 750 kg of $^{nat}TeO_2$ (^{130}Te 33% natural i.a.)
- Array of 1000 cryogenic detectors

THE CUORE DETECTOR

BACKGROUND REDUCTION TECHNIQUES





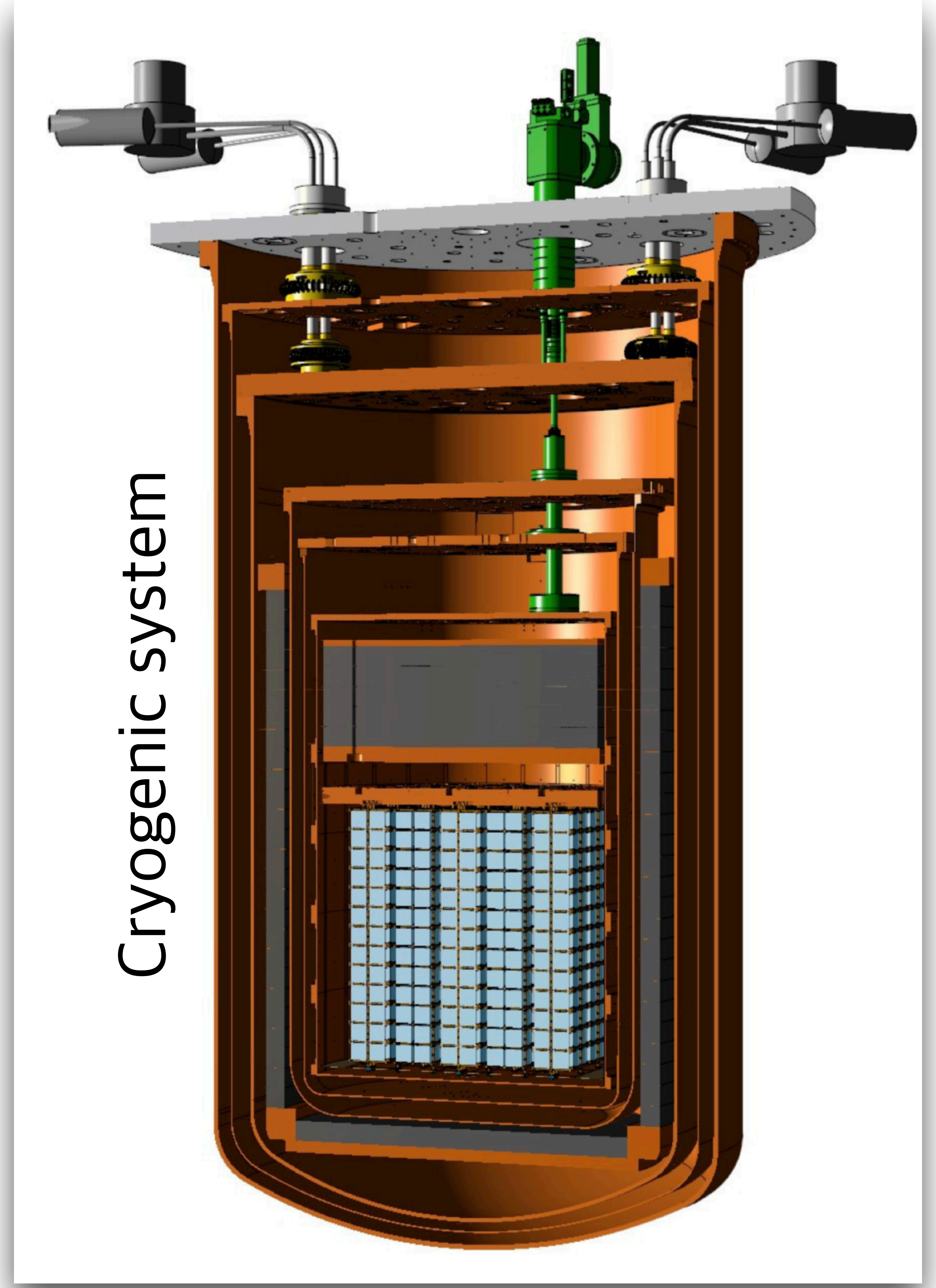
> Internal shield @ 4K - ArchPb

> Material selection - detector purity @ ppt [10^{-12} g/g]

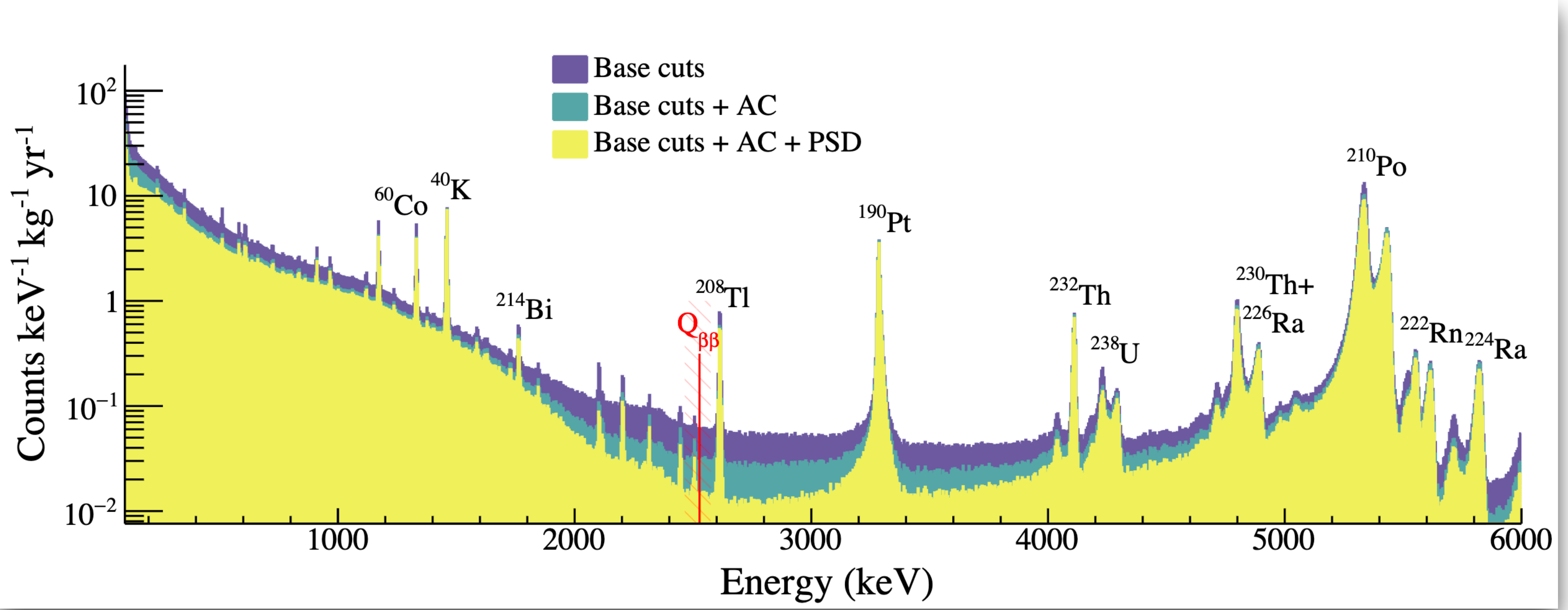
> Anti-coincidence - 1000 detectors array

CUORE $0\nu\beta\beta$ results

Looking for a matter creation process



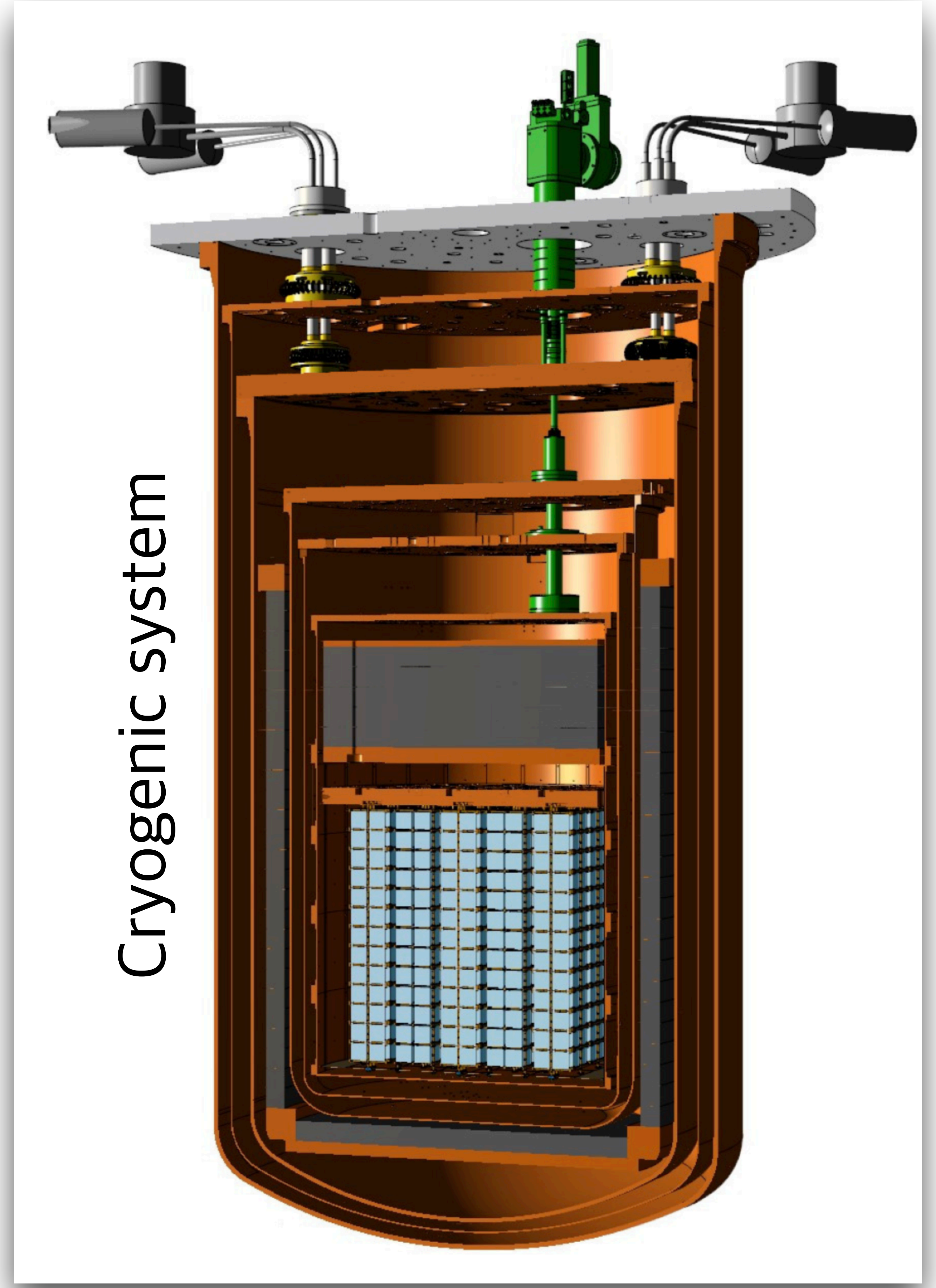
CUORE total detector energy spectrum (exposure 2 ton×y)



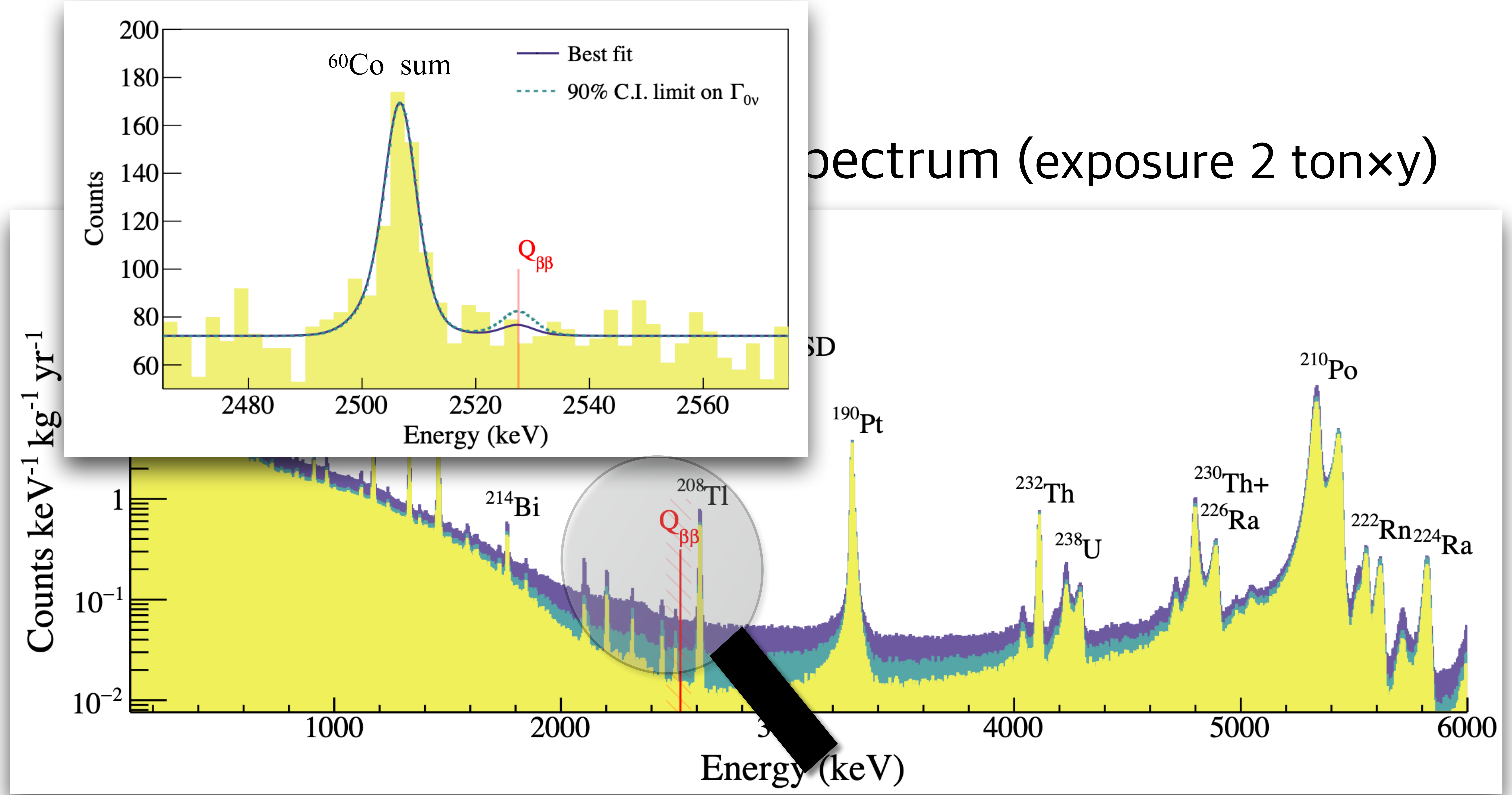
CUORE Coll., ArXiv:2404.04453

CUORE $0\nu\beta\beta$ results

LOOKING FOR A MATTER CREATION PROCESS



pectrum (exposure 2 ton×y)



CUORE Coll., ArXiv:2404.04453

CUORE $0\nu\beta\beta$ RESULTS

LOOKING FOR A MATTER CREATION PROCESS

Results

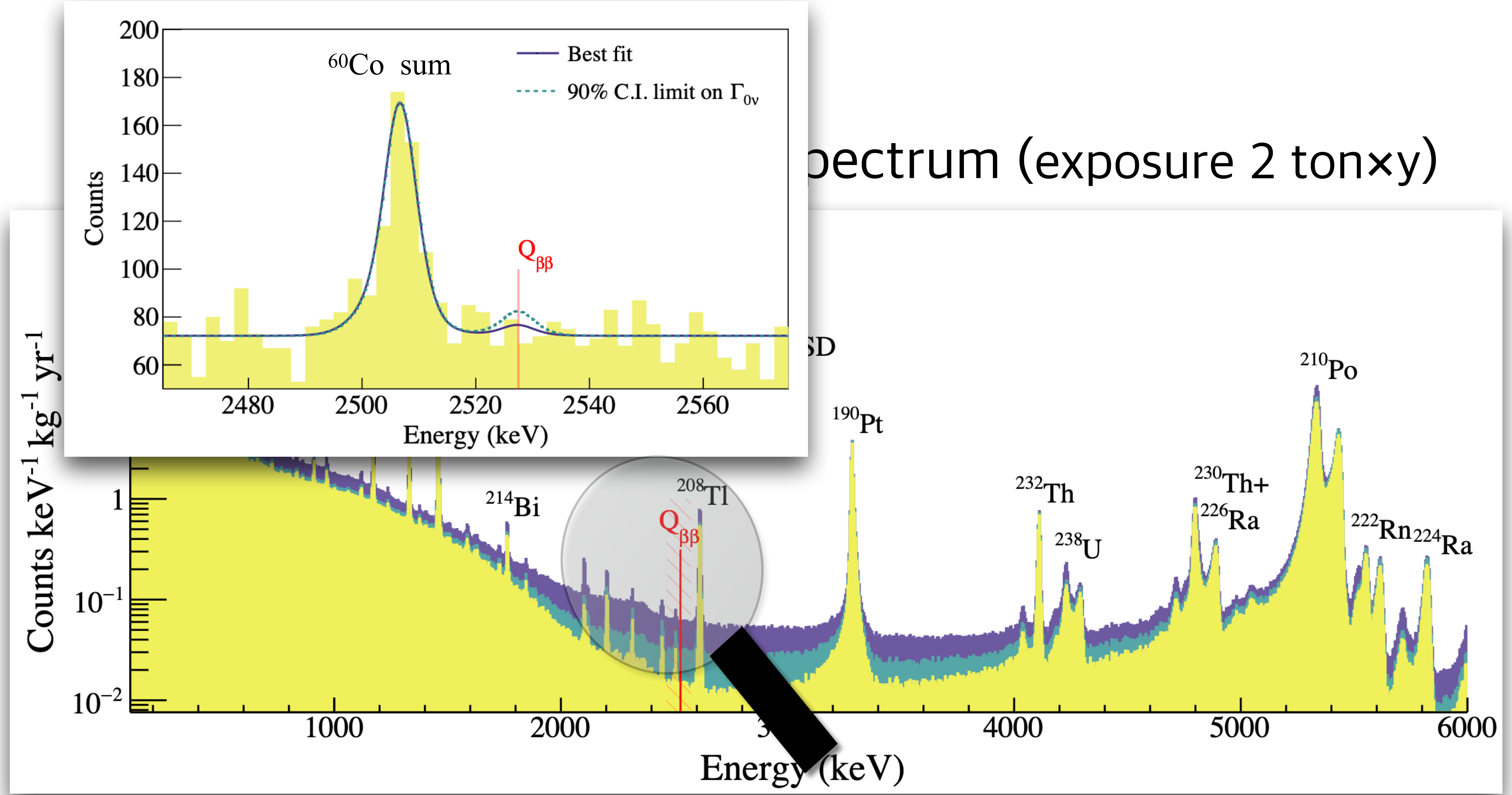
$$T^{0\nu}_{1/2}(^{130}Te) > 4 \times 10^{25} y$$

$$m_{\beta\beta} < (70 - 240)\ meV$$

Detector performance:

FWHM @ ROI - 7.5 keV

Bkg @ ROI - 1.4×10^{-2} c/keV/kg/y



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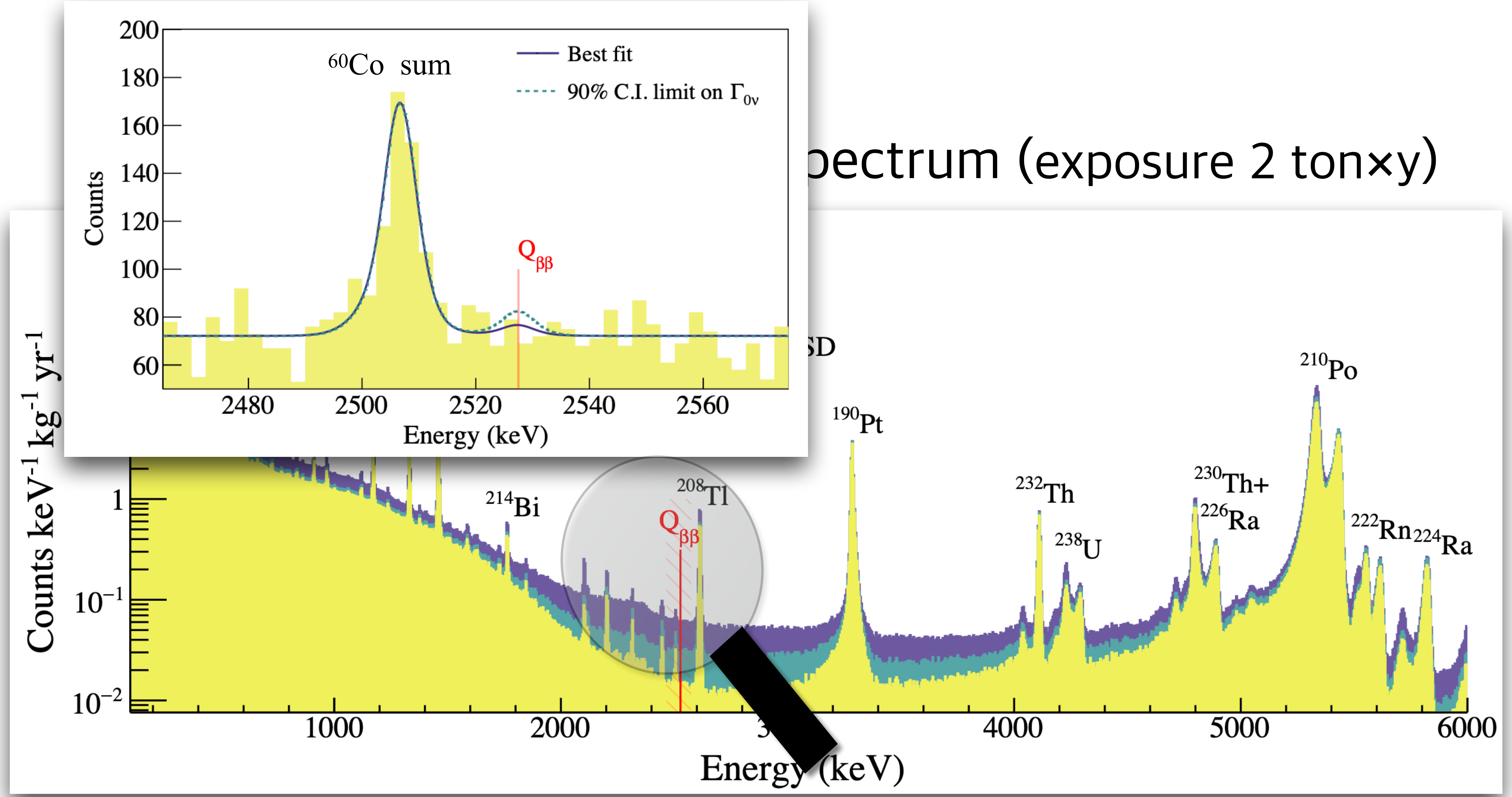

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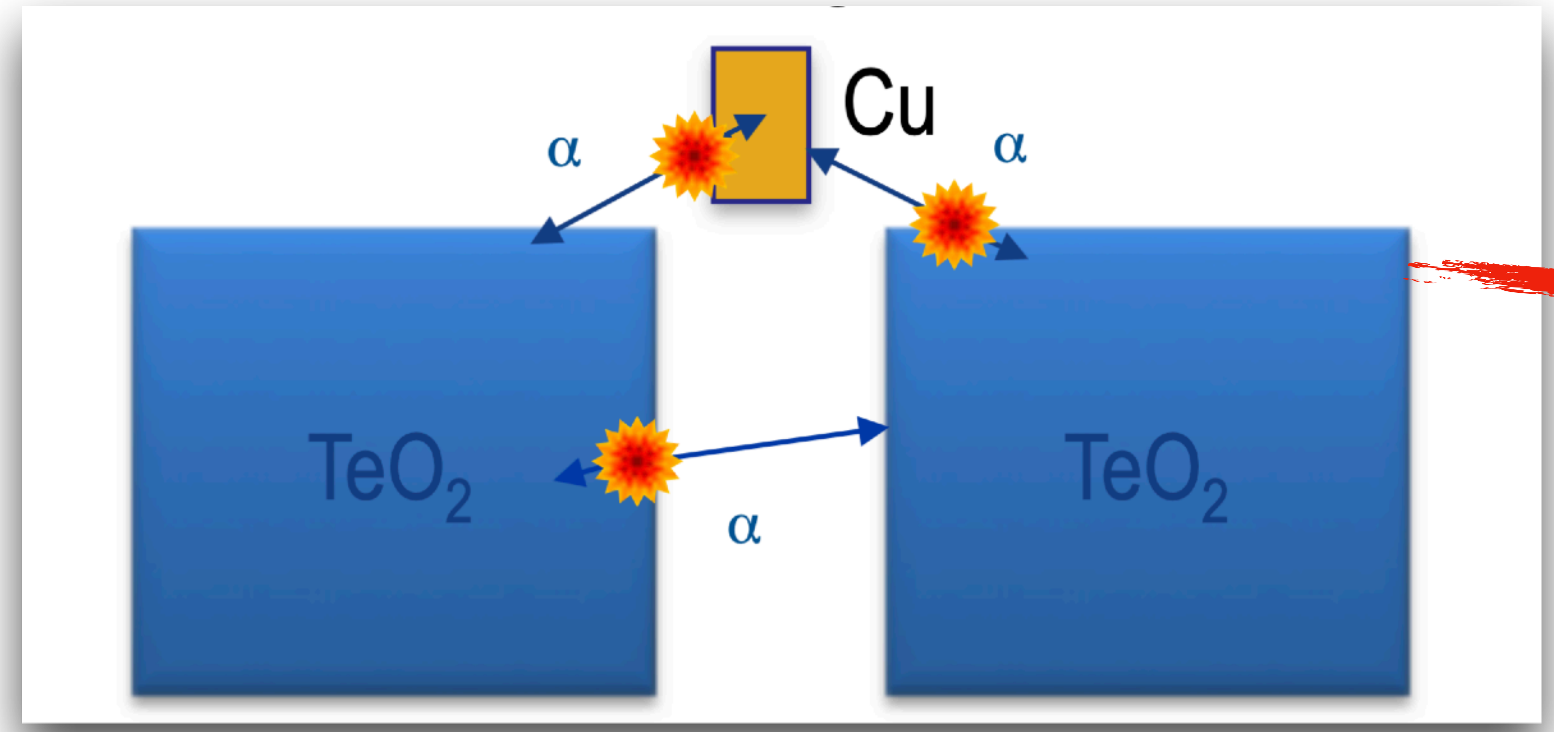
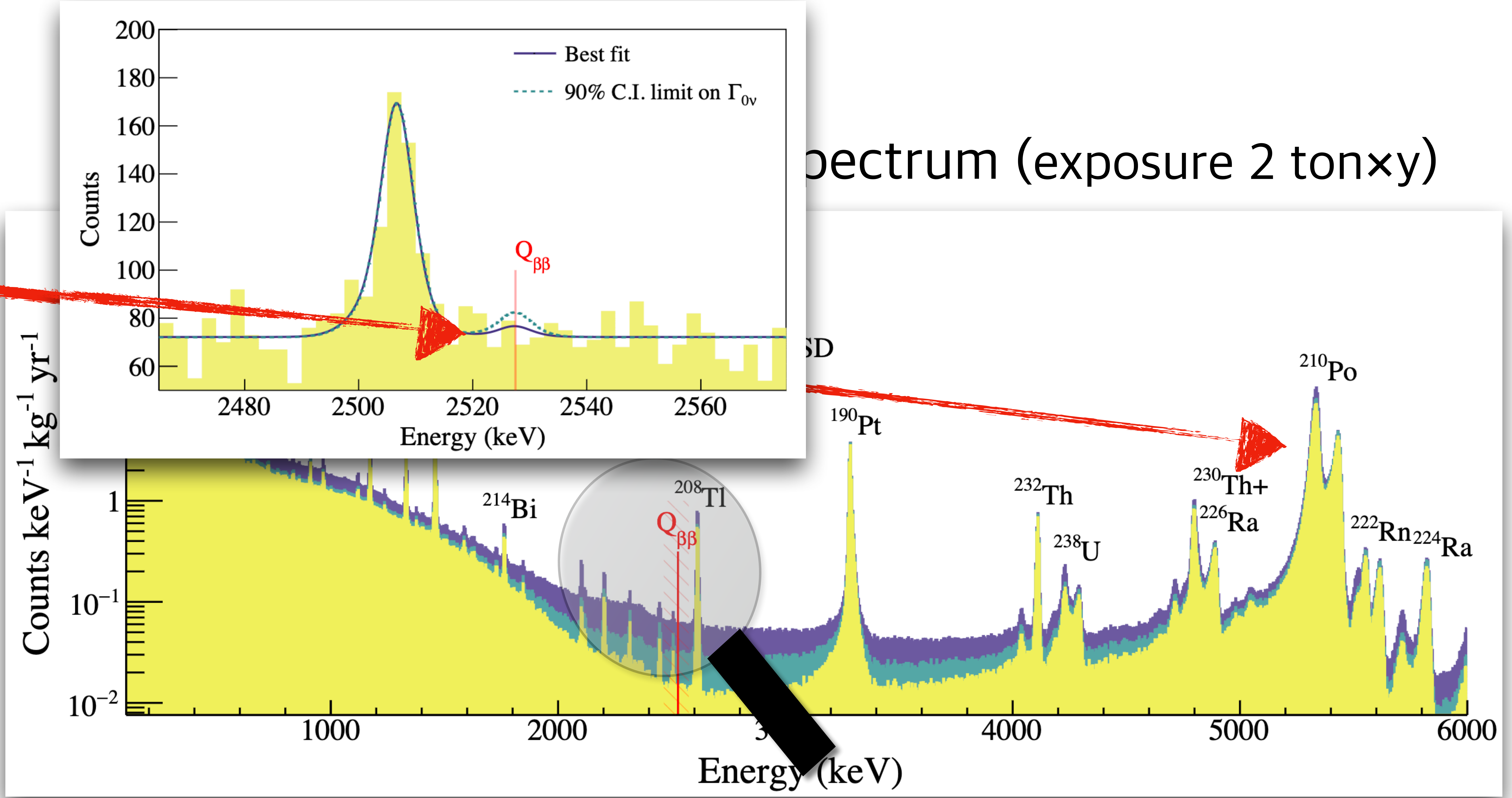
CUORE $0\nu\beta\beta$ RESULTS

LOOKING FOR A MATTER CREATION PROCESS

90% is flat α background



...pectrum (exposure 2 ton×y)



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FWHM @ ROI - 7.5 keV

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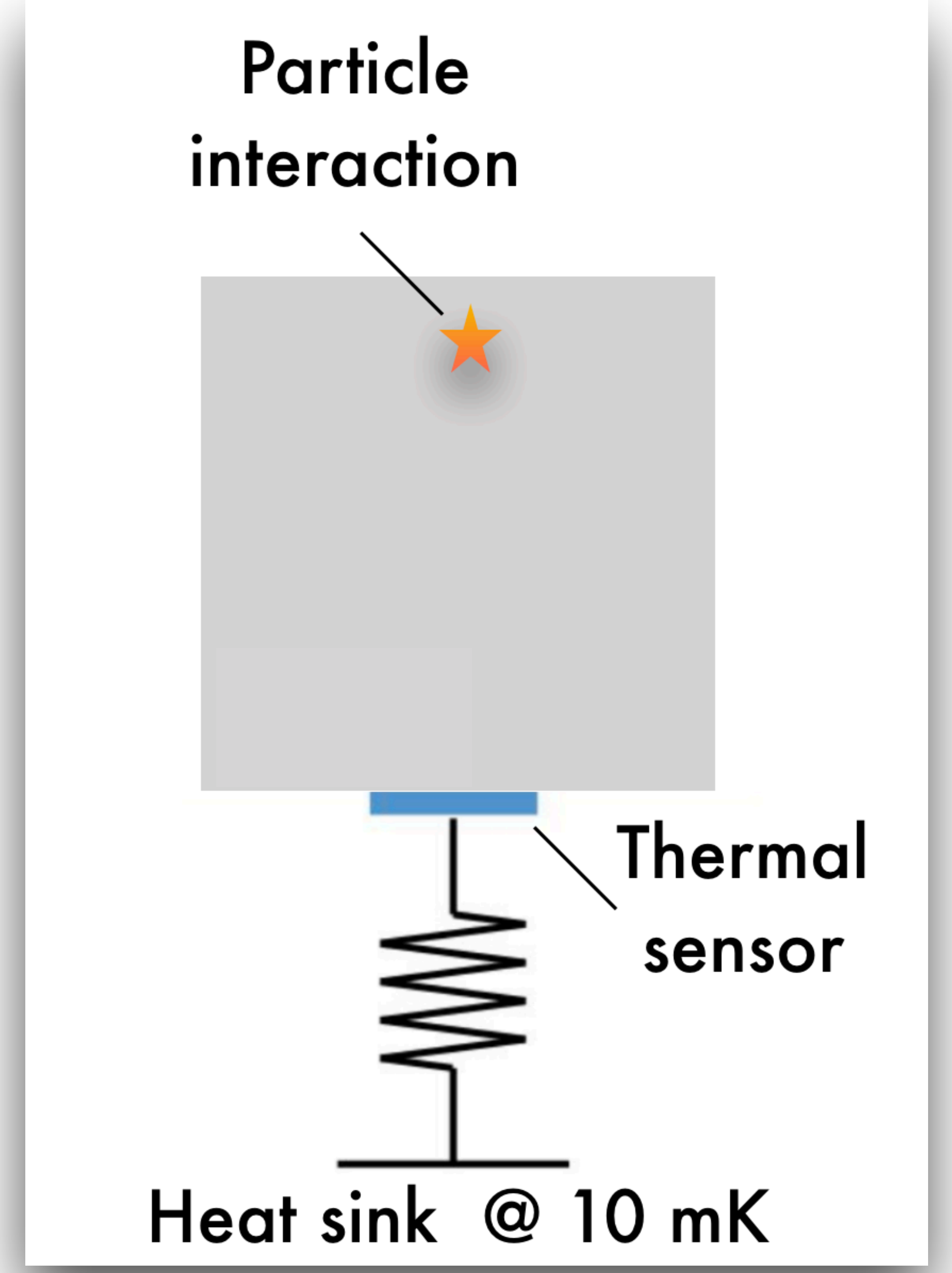
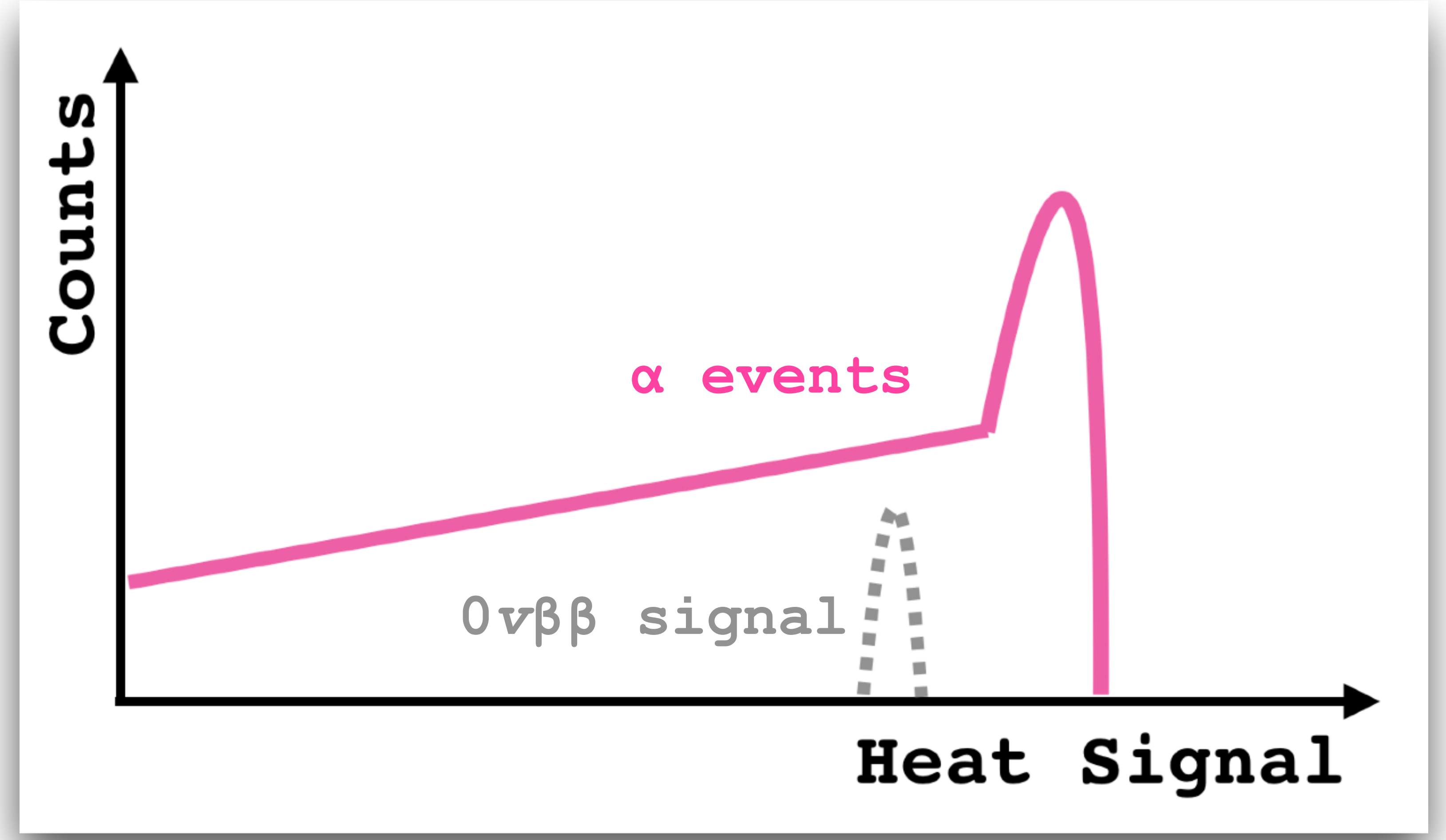
CUORE Coll., ArXiv:2404.04453

BACKGROUNDS SUPPRESSION

SINGLE CHANNEL READ-OUT



Read out of Heat channel

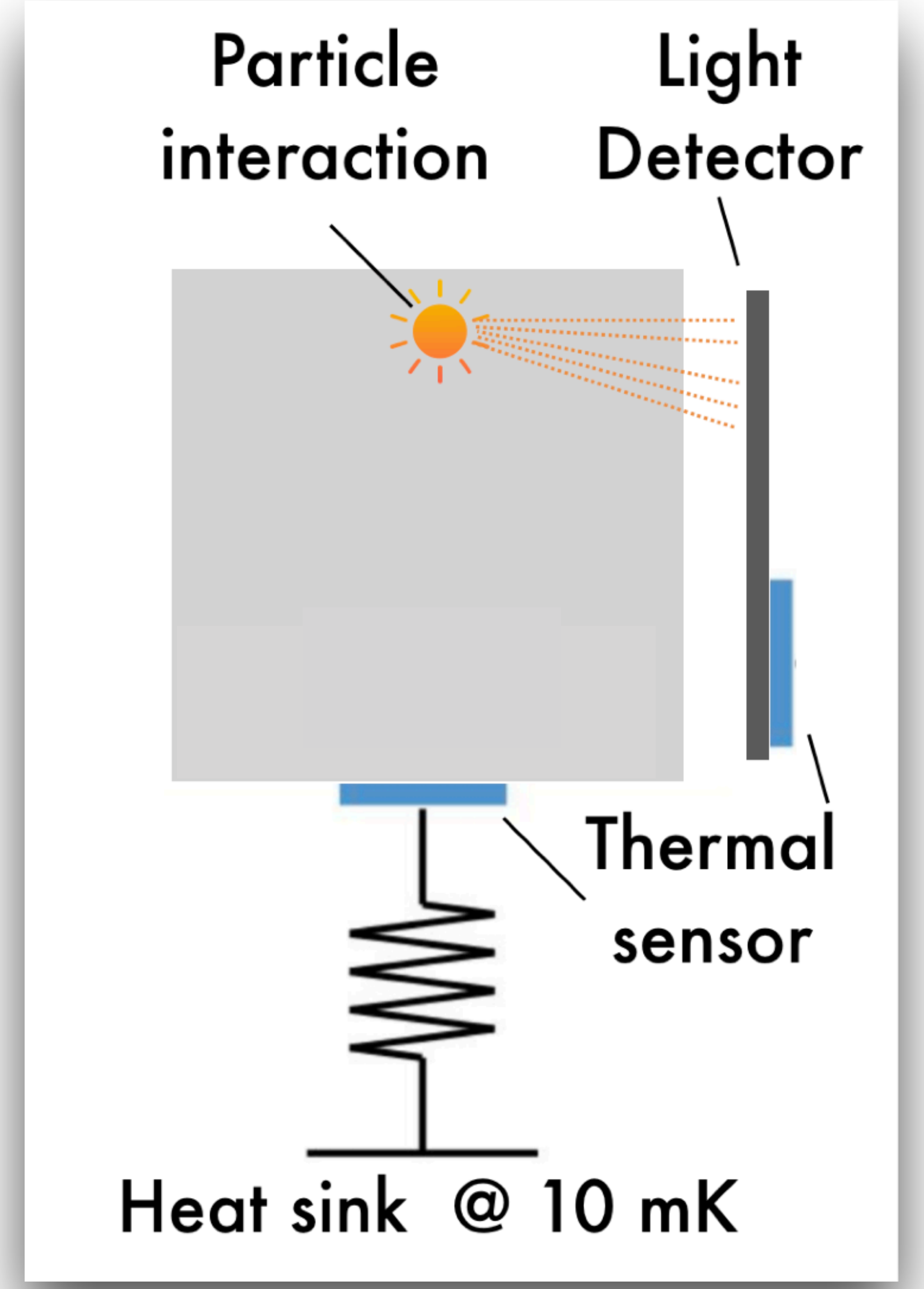


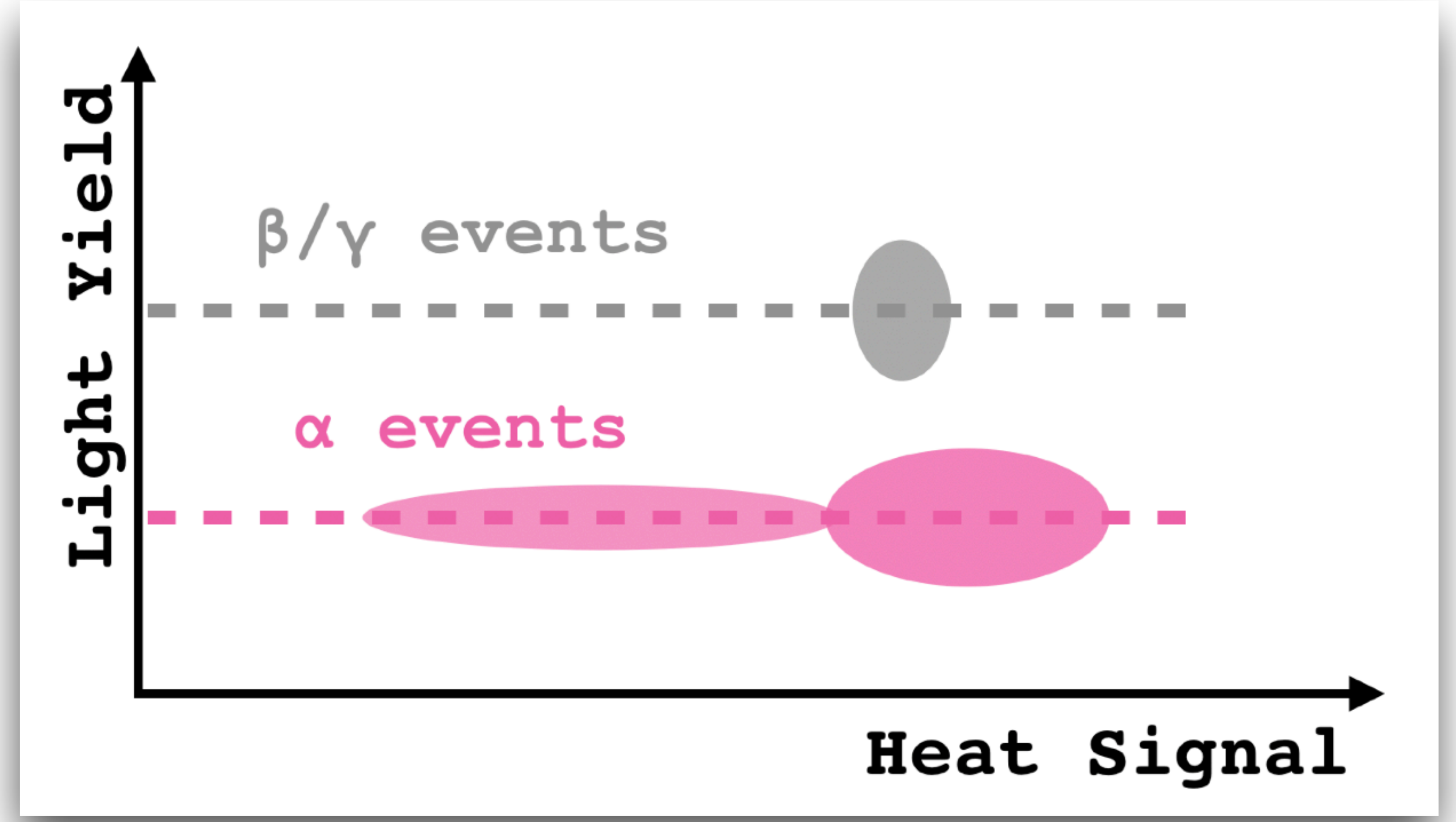
No particle ID

BACKGROUNDS SUPPRESSION

DOUBLE CHANNEL READ-OUT

Read out of Scintillation light **using auxiliary Light Detector**





	PMT	Cryo-det
Quantum efficiency	✘	✔
Energy resolution	✘	✔
Intrinsic radiopurity	✘	✔
Work @ low T	✘	✔
Energy threshold	✔	✘

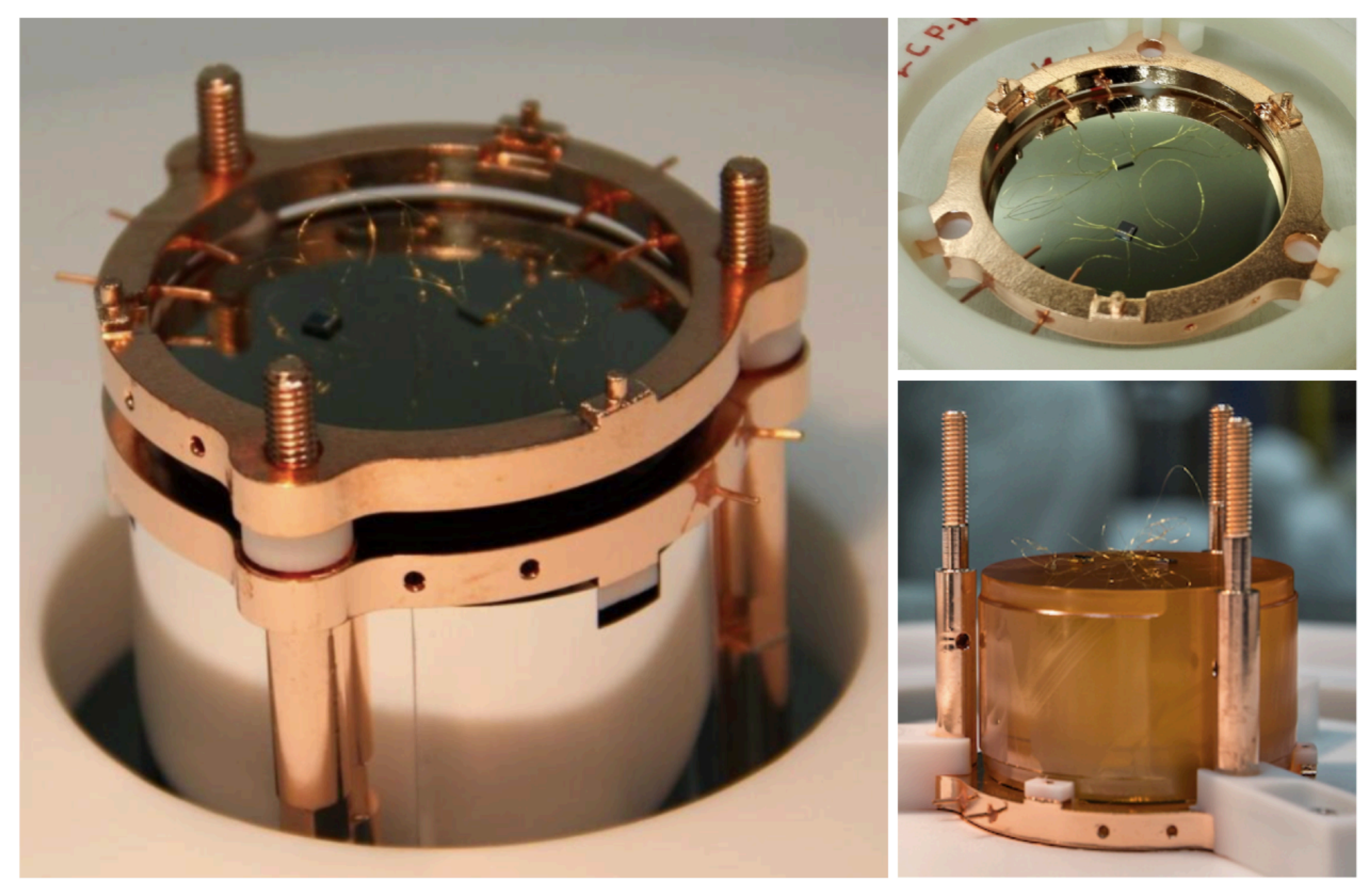
Particle ID

CUORE successor: CUPID

Cuore Upgrade with Particle ID

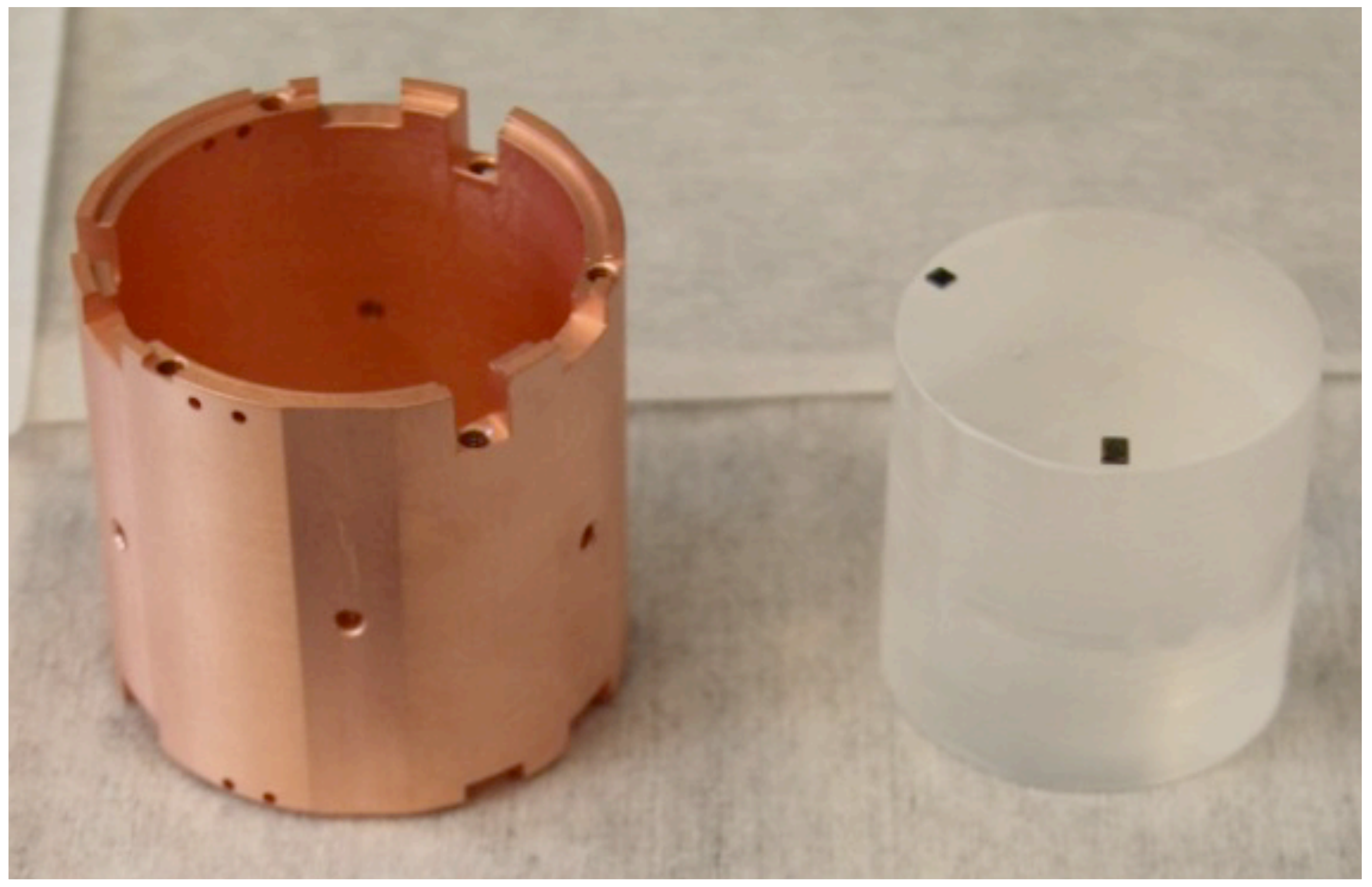
merging 3 technologies

CUPID-0: particle ID with **LD**



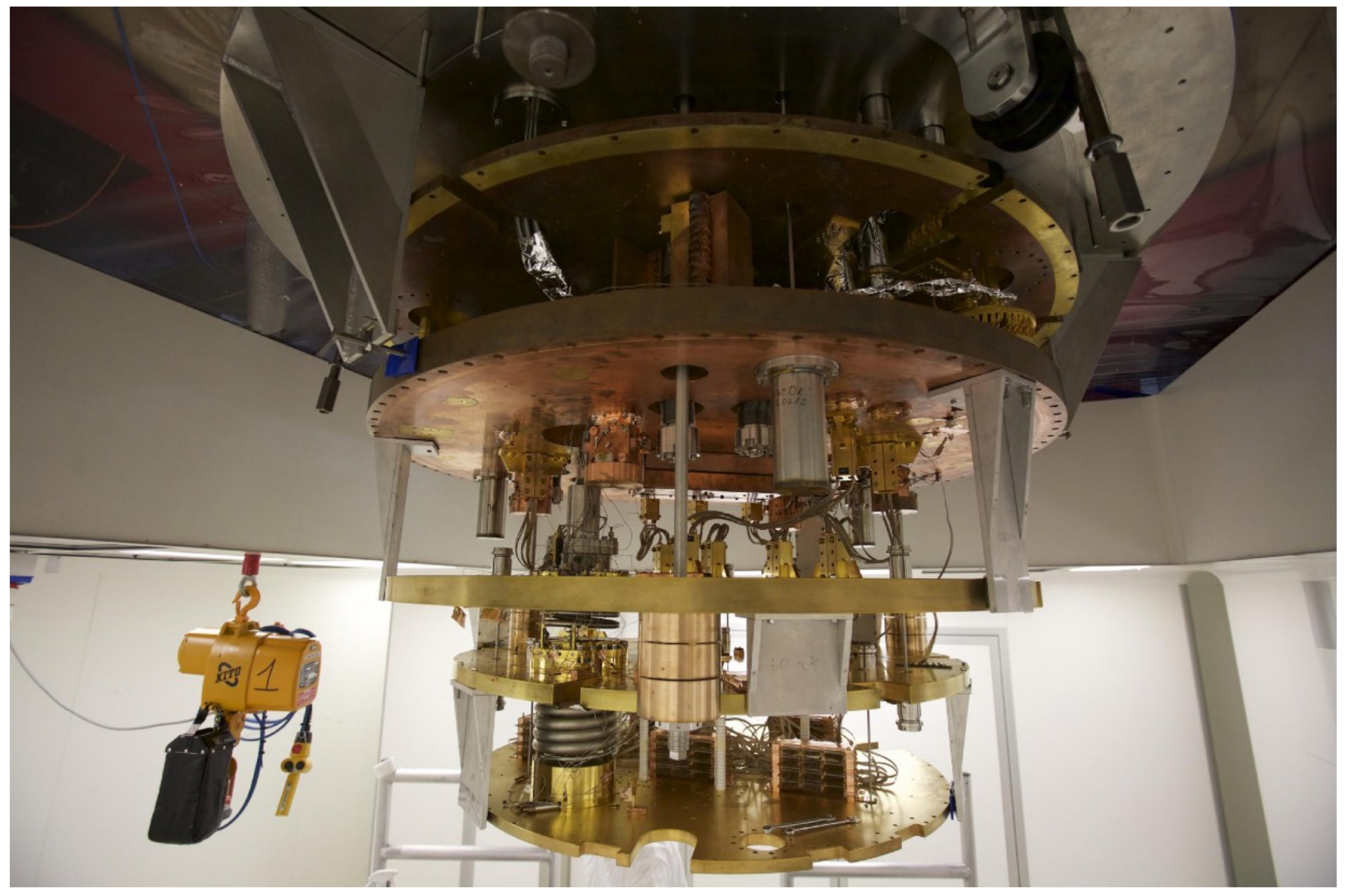
> lowest bkg in a cryo-det:
> 3×10^{-3} c/keV/kg/y @ ROI

CUPID-Mo: $Li_2{}^{100}MoO_4$ target



> excellent radiopurity:
> ^{232}Th: <2 uBq/kg ; ^{238}U: <3 uBq/kg

CUORE: cryogenic infrastructure



> Continuous operation since 2018

O. Azzolini, **LP** et al., Eur. Phys. J. C (2018) 78:428

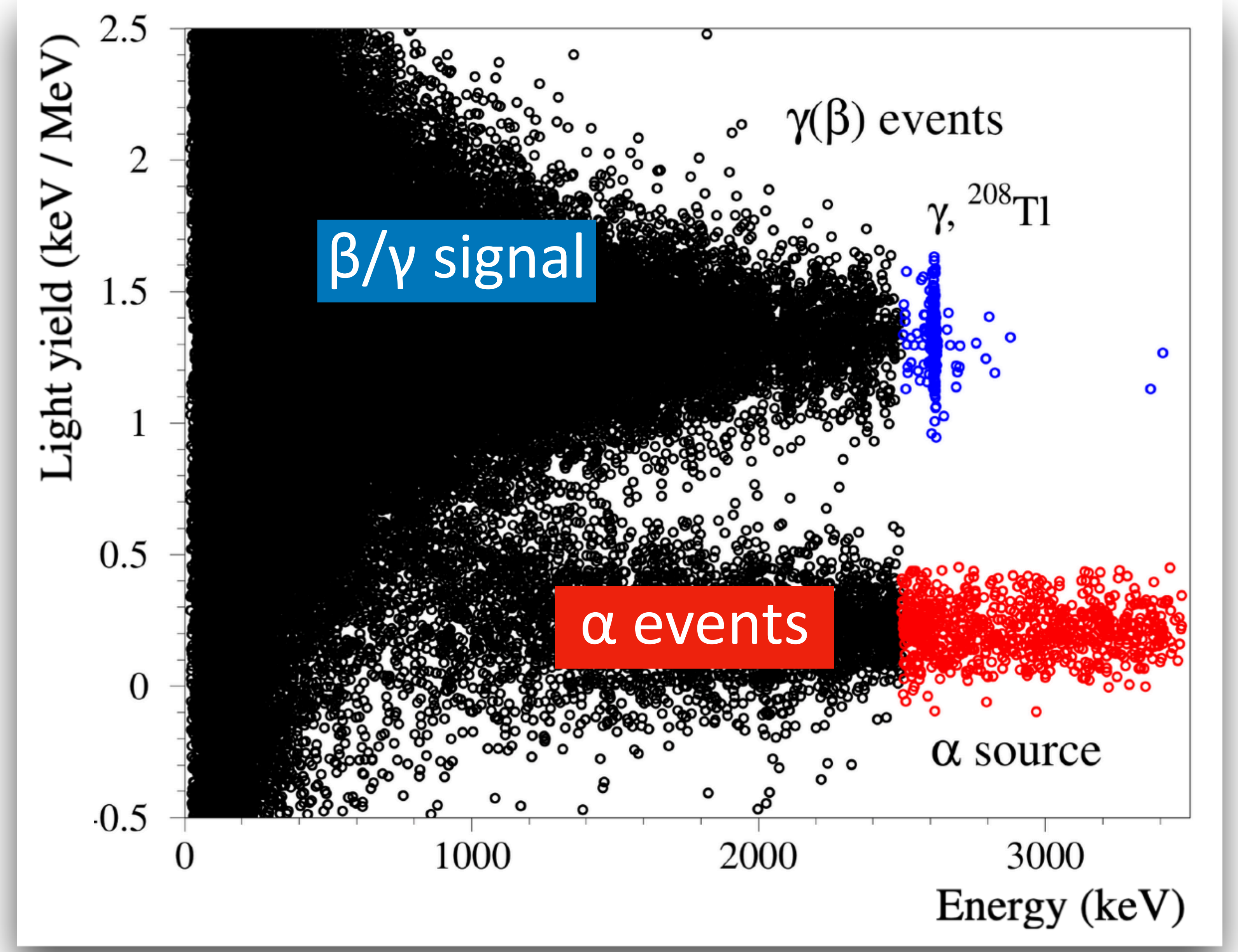
L Cardani, **LP** *et al* 2013 *JINST* 8 P10002

CUORE Coll., *Nature* 604, pages 53–58 (2022)

CUORE Upgrade with Particle ID

replacing $^{nat}TeO_2$ with $Li_2{}^{100}MoO_4$

Detector performance

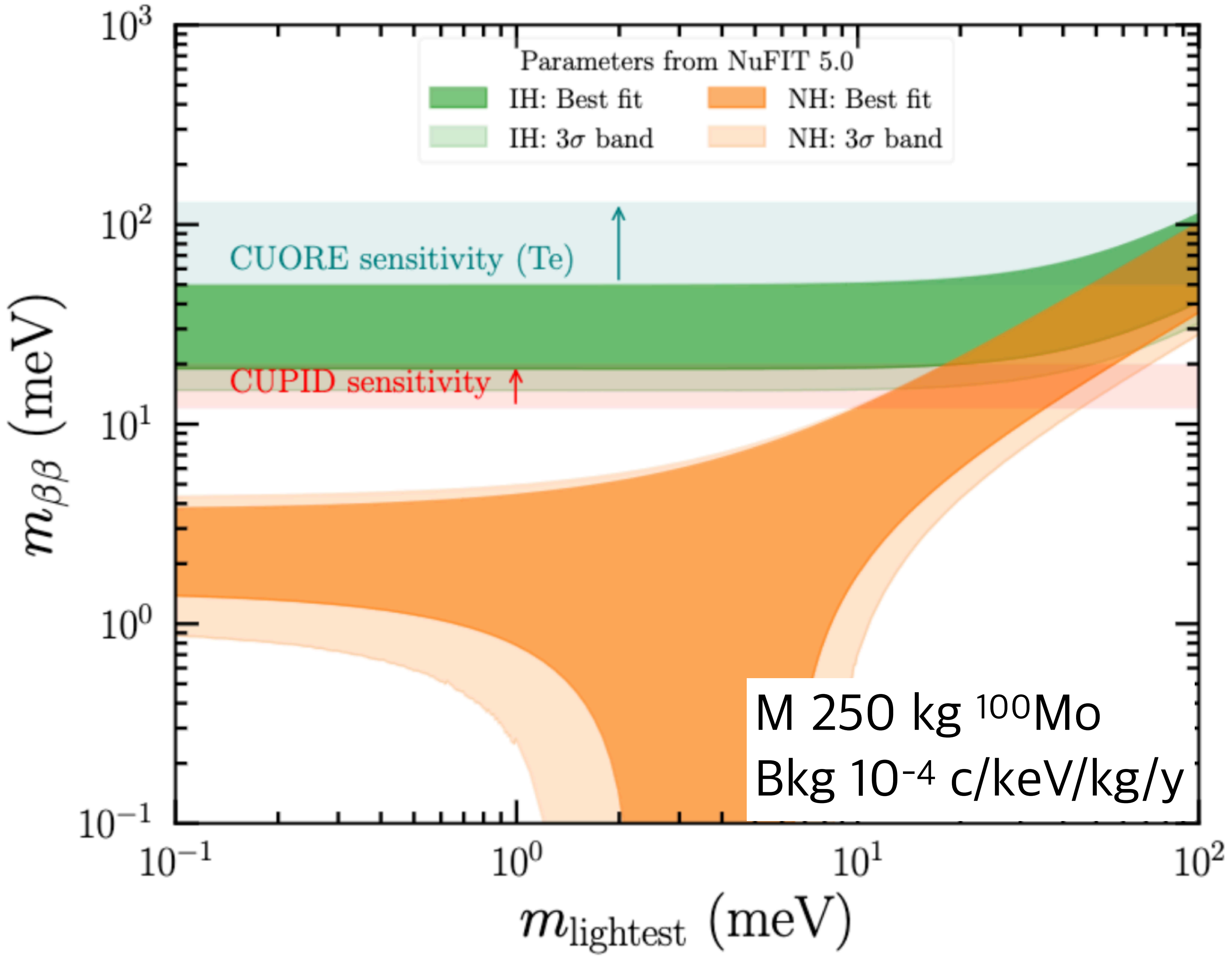


CUPID Coll., *et al* 2021 *JINST* 16 P02037

CUPID

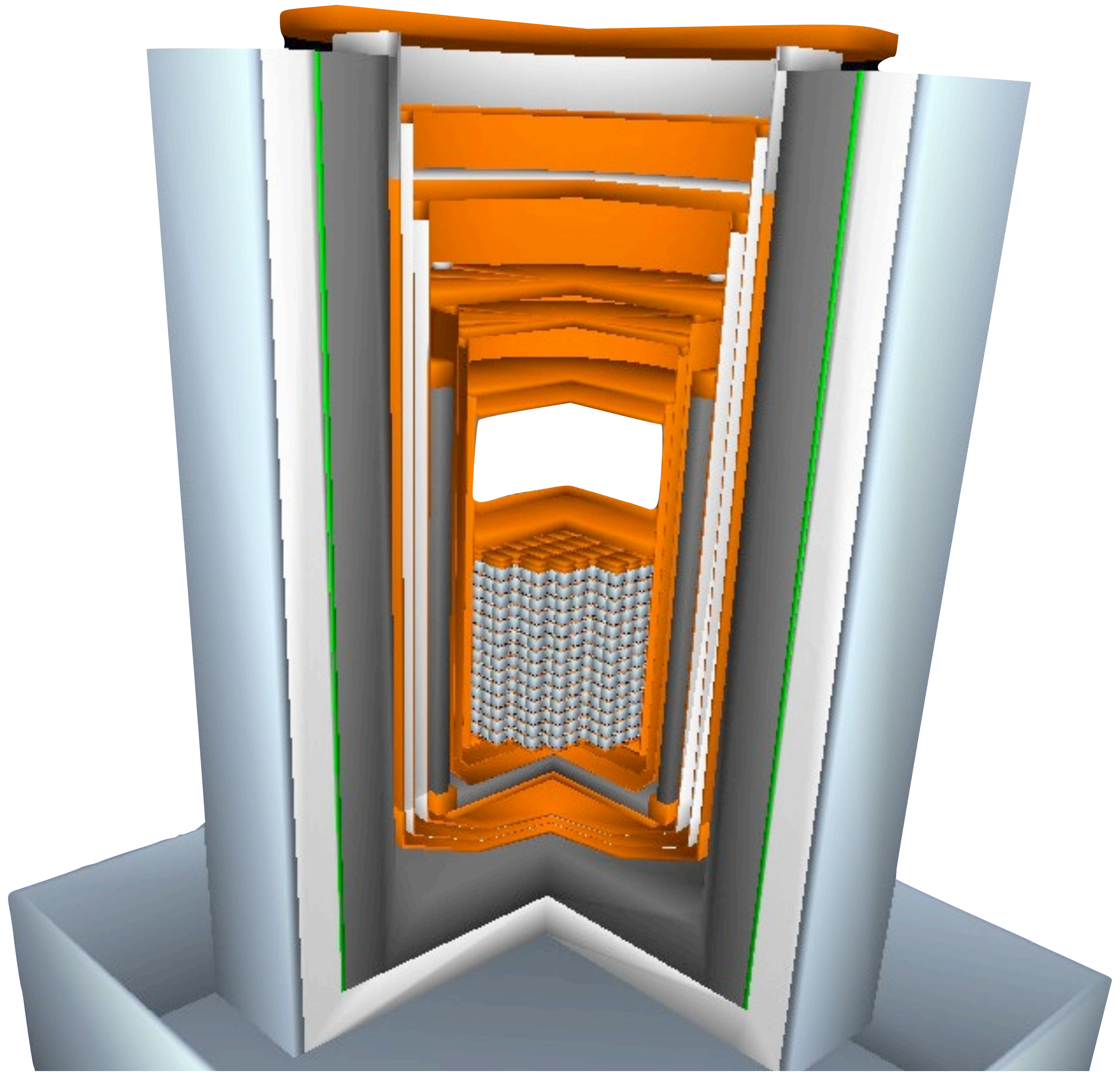
$$T_{1/2}^{0\nu\beta\beta}(^{100}\mathrm{Mo}) = 10^{27}\ y$$

$m_{\beta\beta}$ =12-20 meV



CUPID pre-CDR - ArXiv:1907.09376

CUORE infrastructure background



Open questions

What is matter ?

Neutrino properties

Astroparticle observatory

Dark Matter searches

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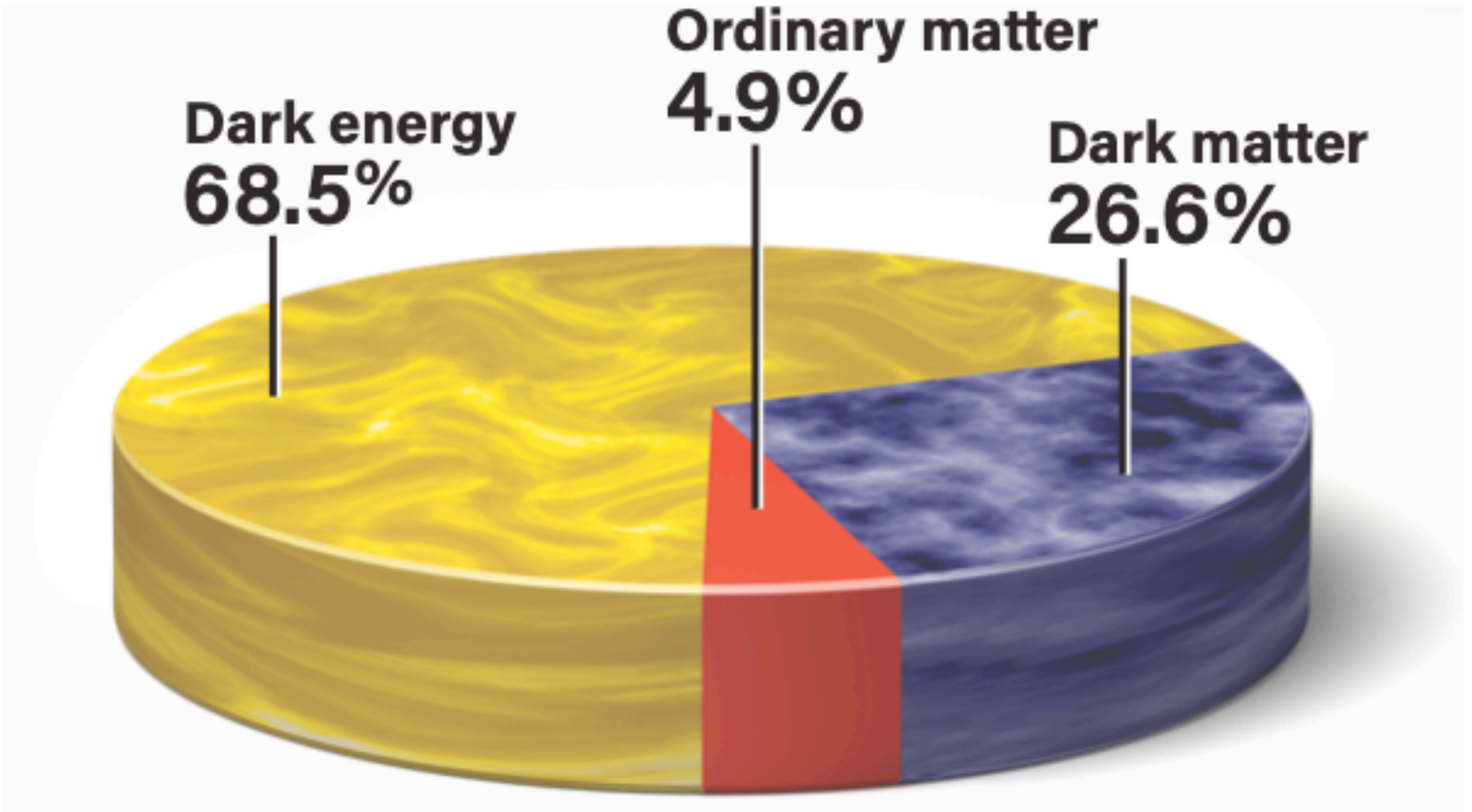
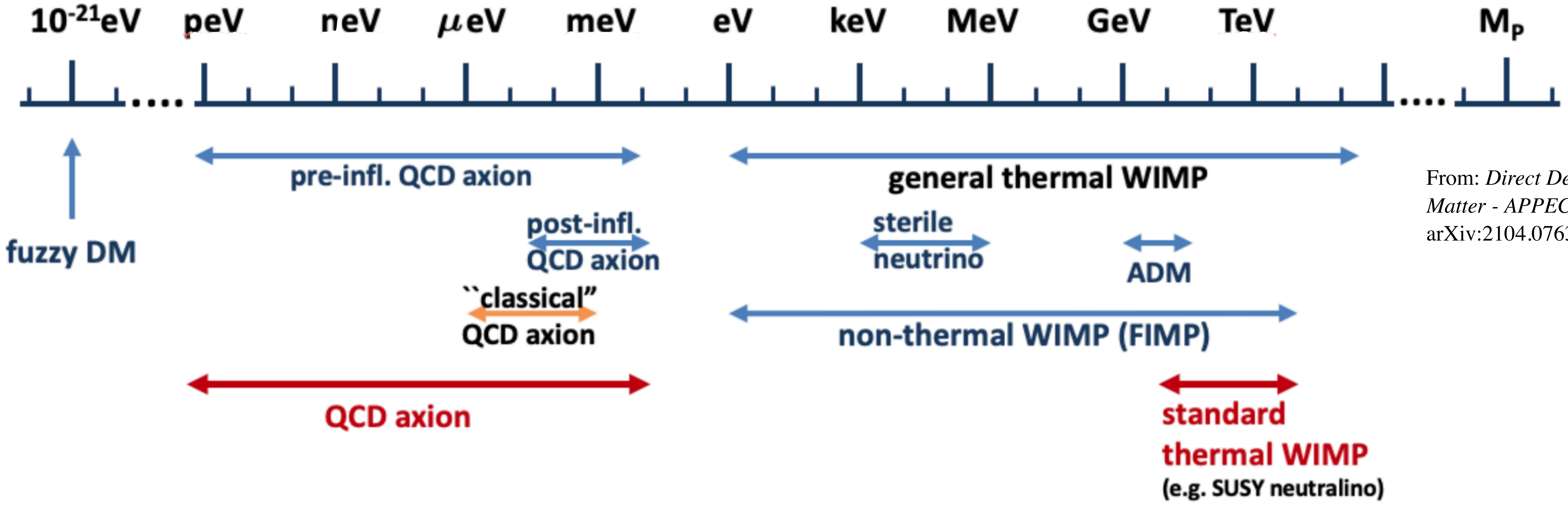
What is matter ?

you mean Dark Matter ...



Astronomy: Roen Kelly, after NIST

Great variety of DM candidates

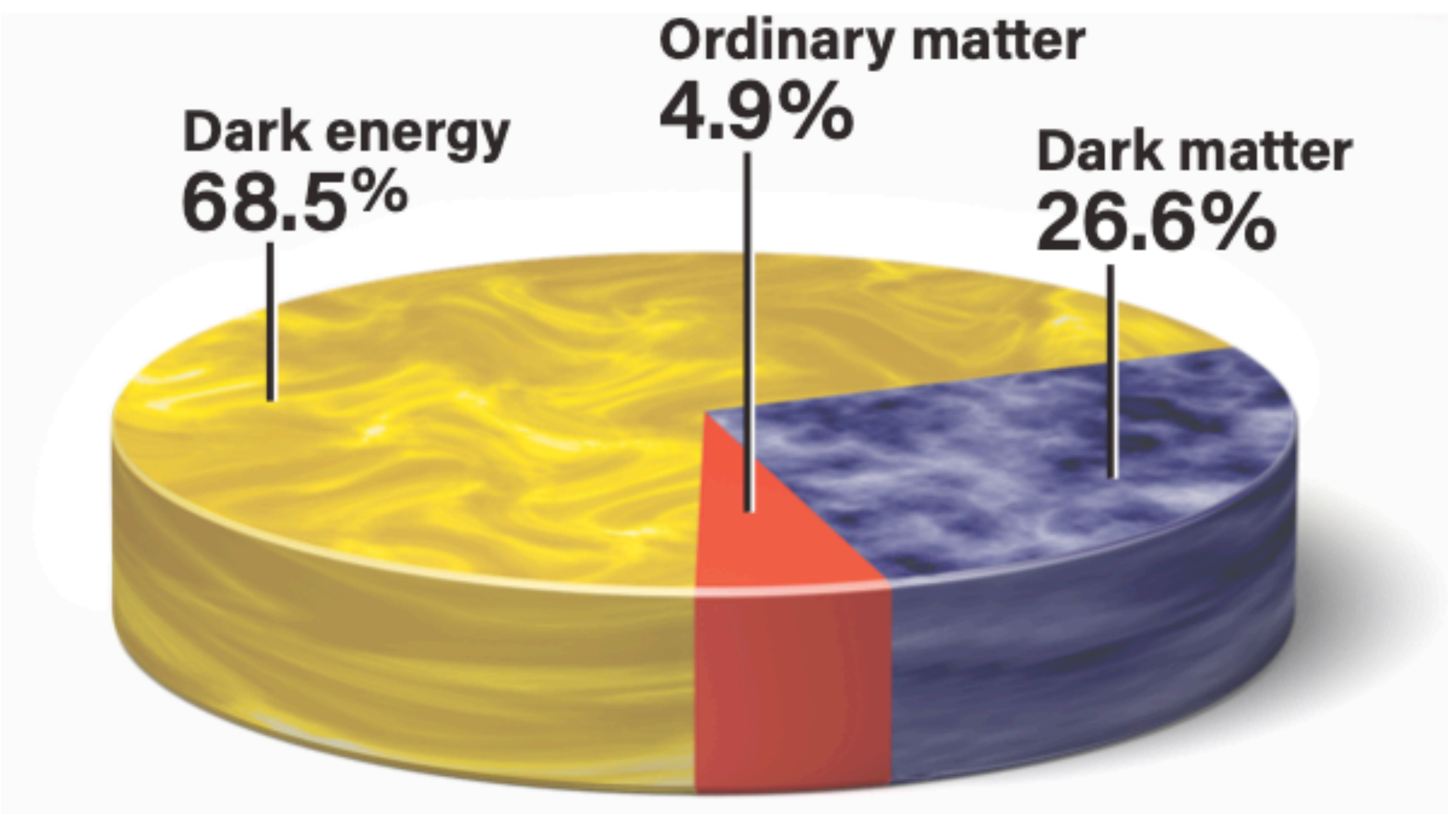


From: *Direct Detection of Dark Matter - APPEC Committee Report* arXiv:2104.07634

Great variety of theoretically motivated dark matter particle candidates

What is matter ?

you mean Dark Matter ...



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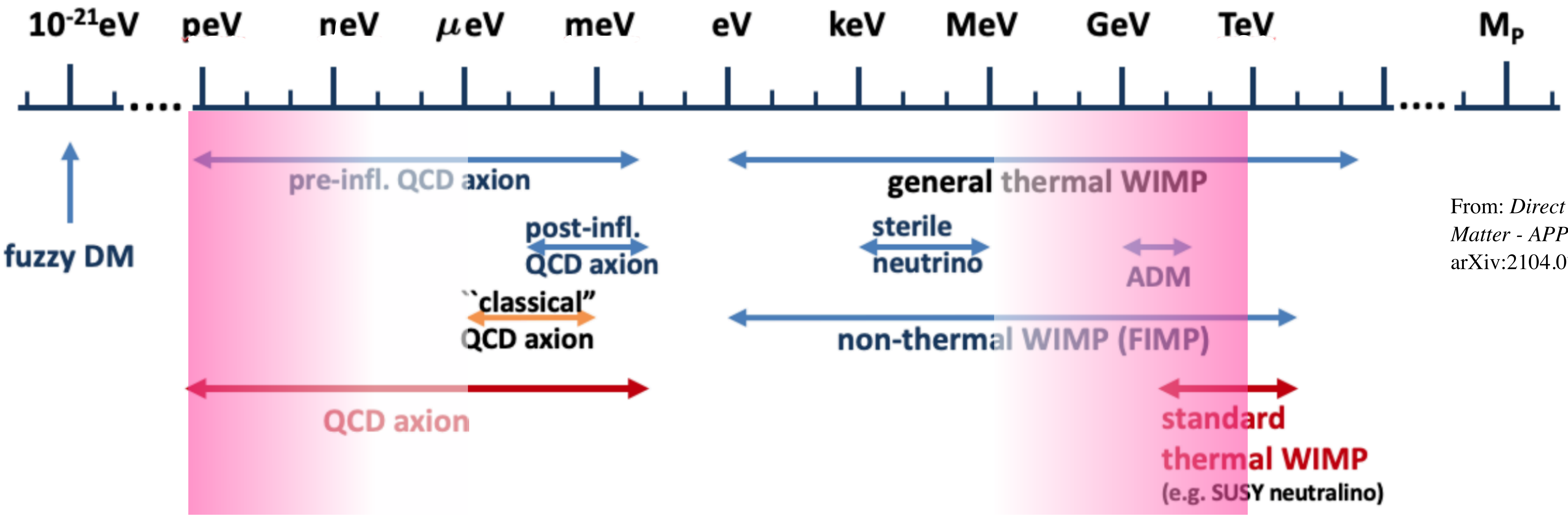
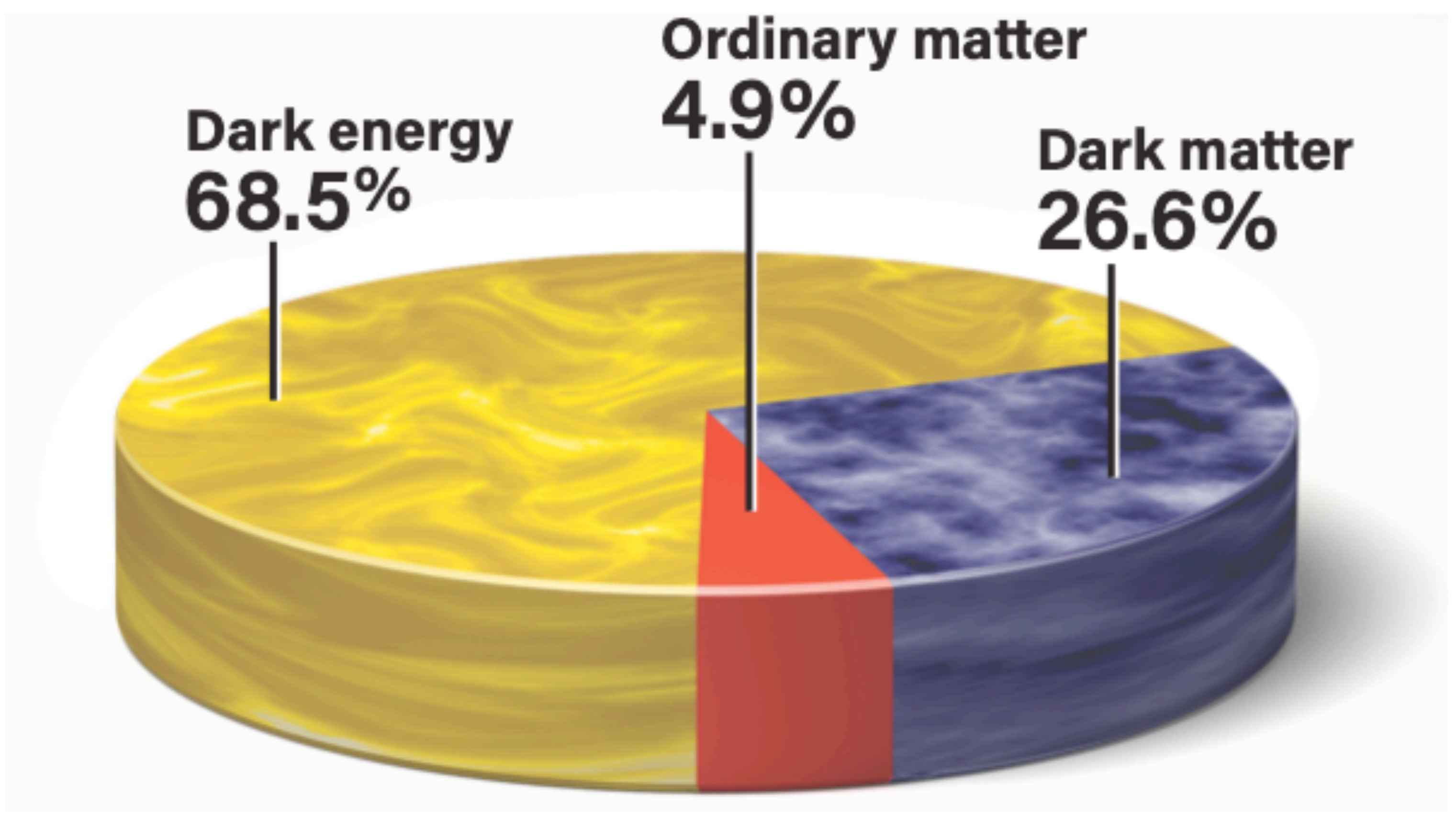


From: *Direct Detection of Dark Matter - APPEC Committee Report* arXiv:2104.07634

Experimental efforts

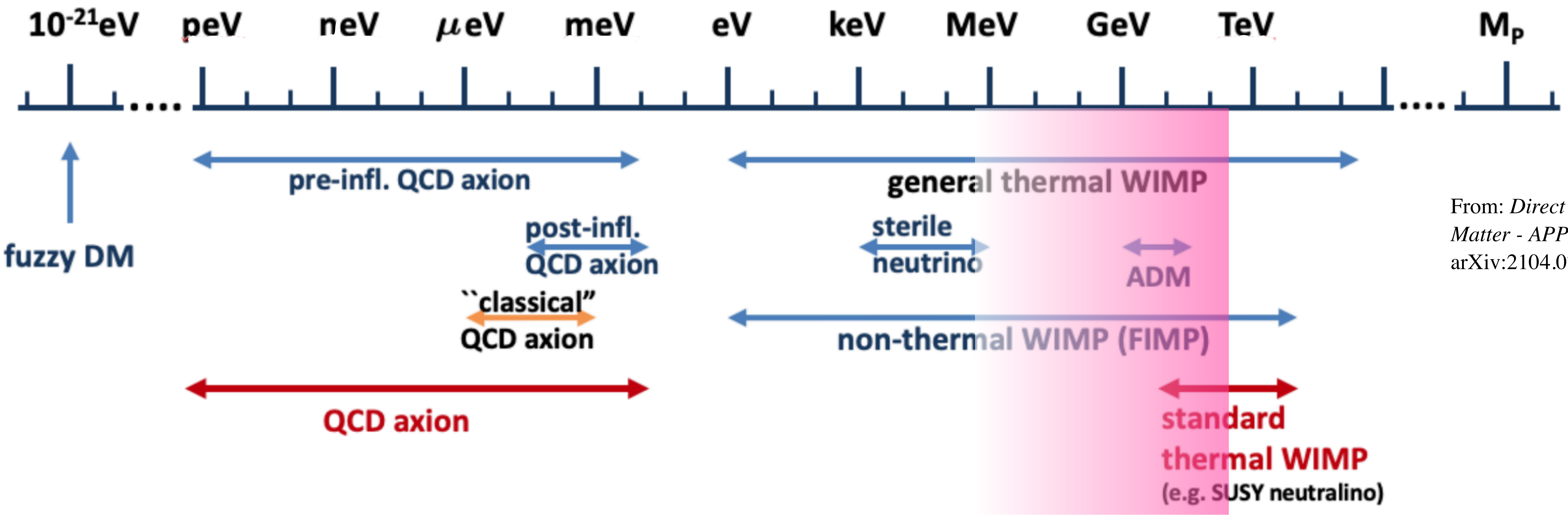
What is matter ?

you mean Dark Matter ...



Astronomy: Roen Kelly, after NIST

Great variety of DM candidates

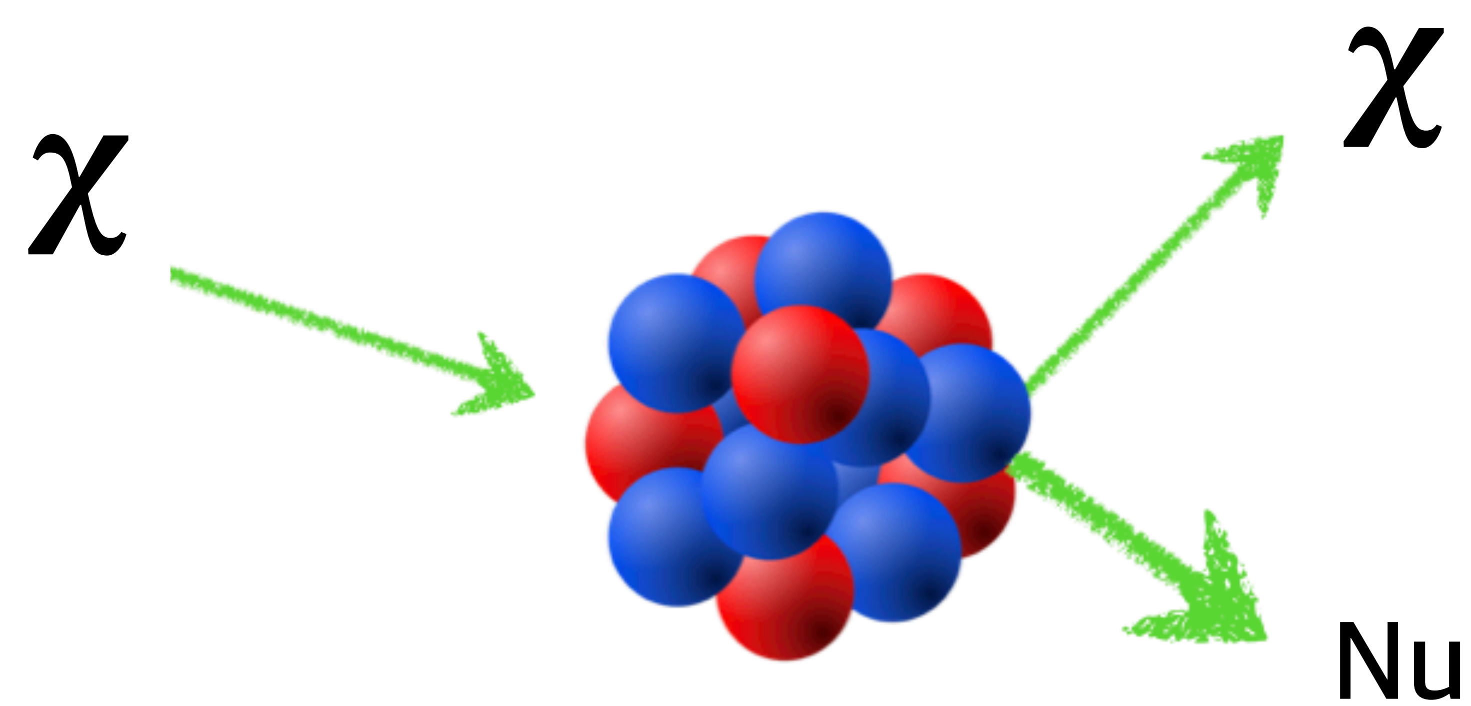


From: *Direct Detection of Dark Matter - APPEC Committee Report* arXiv:2104.07634

WIMP-like
(Weakly Interacting Massive Particles)

How to look for DM

Low energy searches



Nuclear recoil
E_R ~ev/keV

> Elastic and coherent scattering (spin independent)

> Low interaction cross-section

cross-section

$$\sigma_0 = \frac{4\mu_{red}^2}{\pi} F^2(q)\ A^2\ f^2$$

Nuclear Form factor

Atomic number

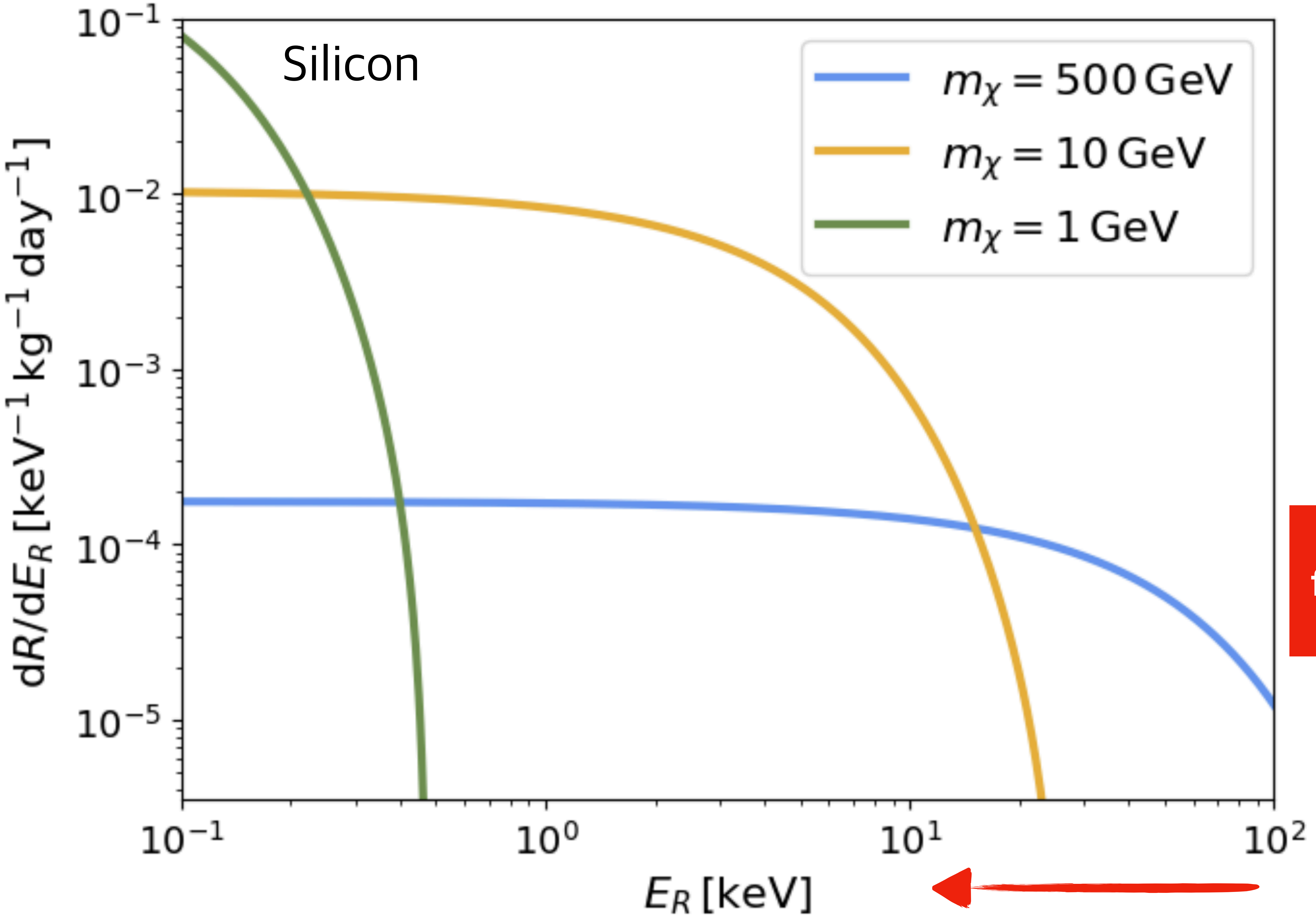
Effective coupling

The DM signal

THE CHALLENGE

DM nuclear recoil energy spectrum for σ = **10^-7 pb**

low interaction rate

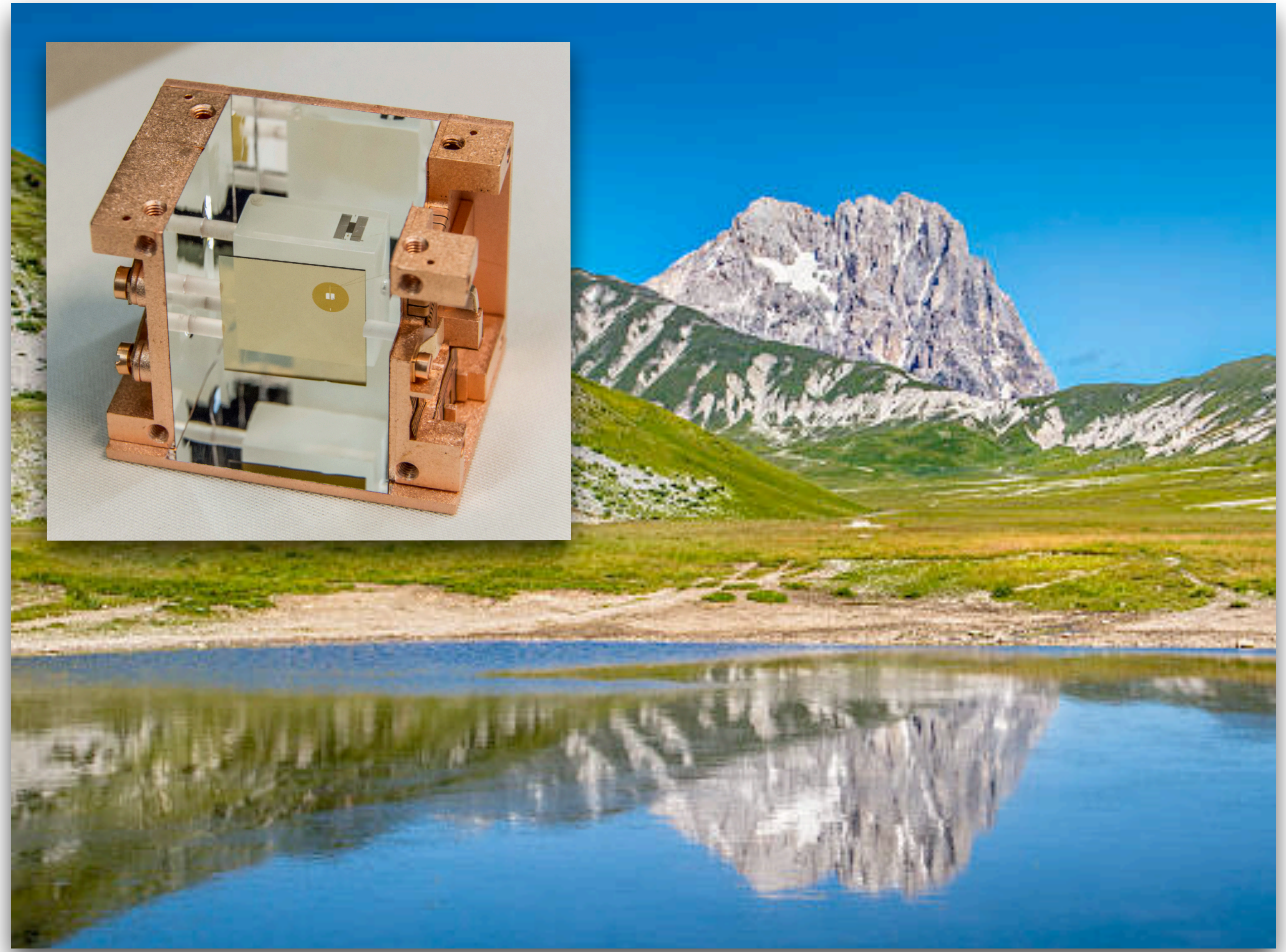


To get to σ~10^{-7} pb for 500 GeV DM, we need 10 ton for 1 GeV DM, we need 10 kg

low-energy threshold

CRESST Experiment

Sub-GeV Dark Matter explorer



- Field driver for light-DM searches
- Low-threshold cryo-detectors
- @ underground of LNGS (3600 m w.e.)
- International collaboration (50+ members)

TUM

INFN

COMENIUS UNIVERSITY BRATISLAVA

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

TU WIEN TECHNISCHE UNIVERSITÄT WIEN

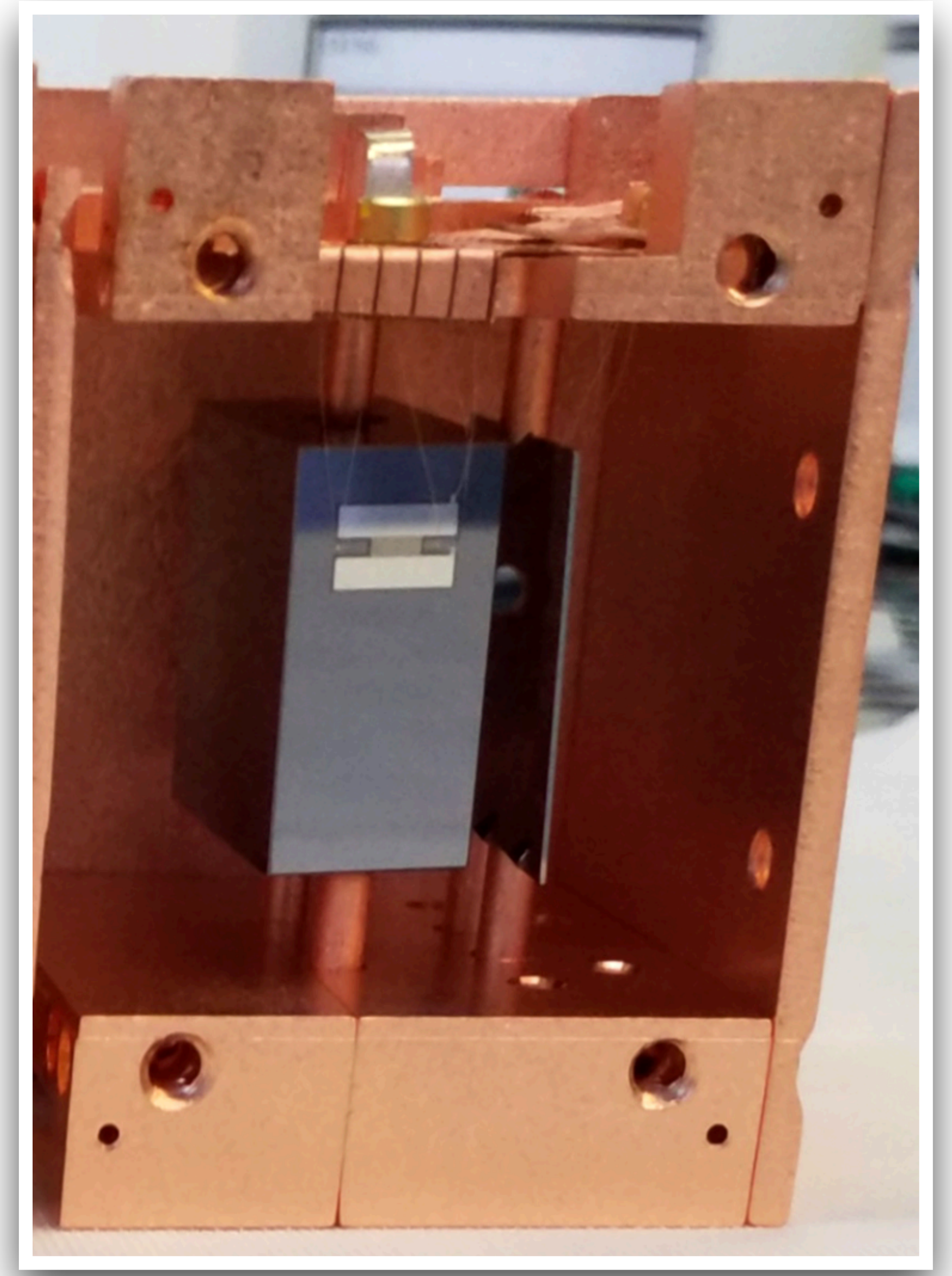
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

UNIVERSITY OF OXFORD

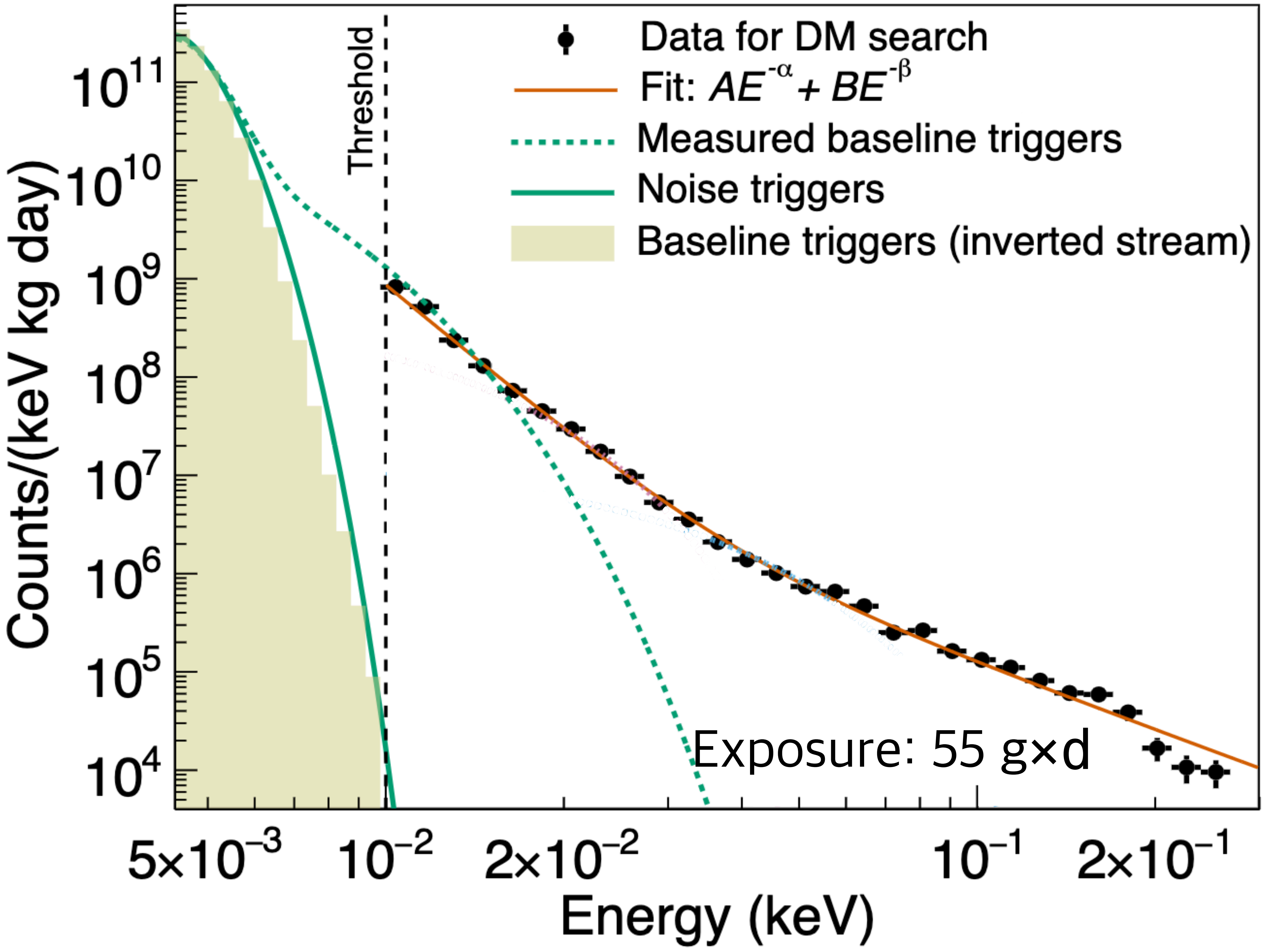
CRESST-III physics results

Leading the sector

Si wafer detector: 0.35 g



CRESST-III background energy spectrum

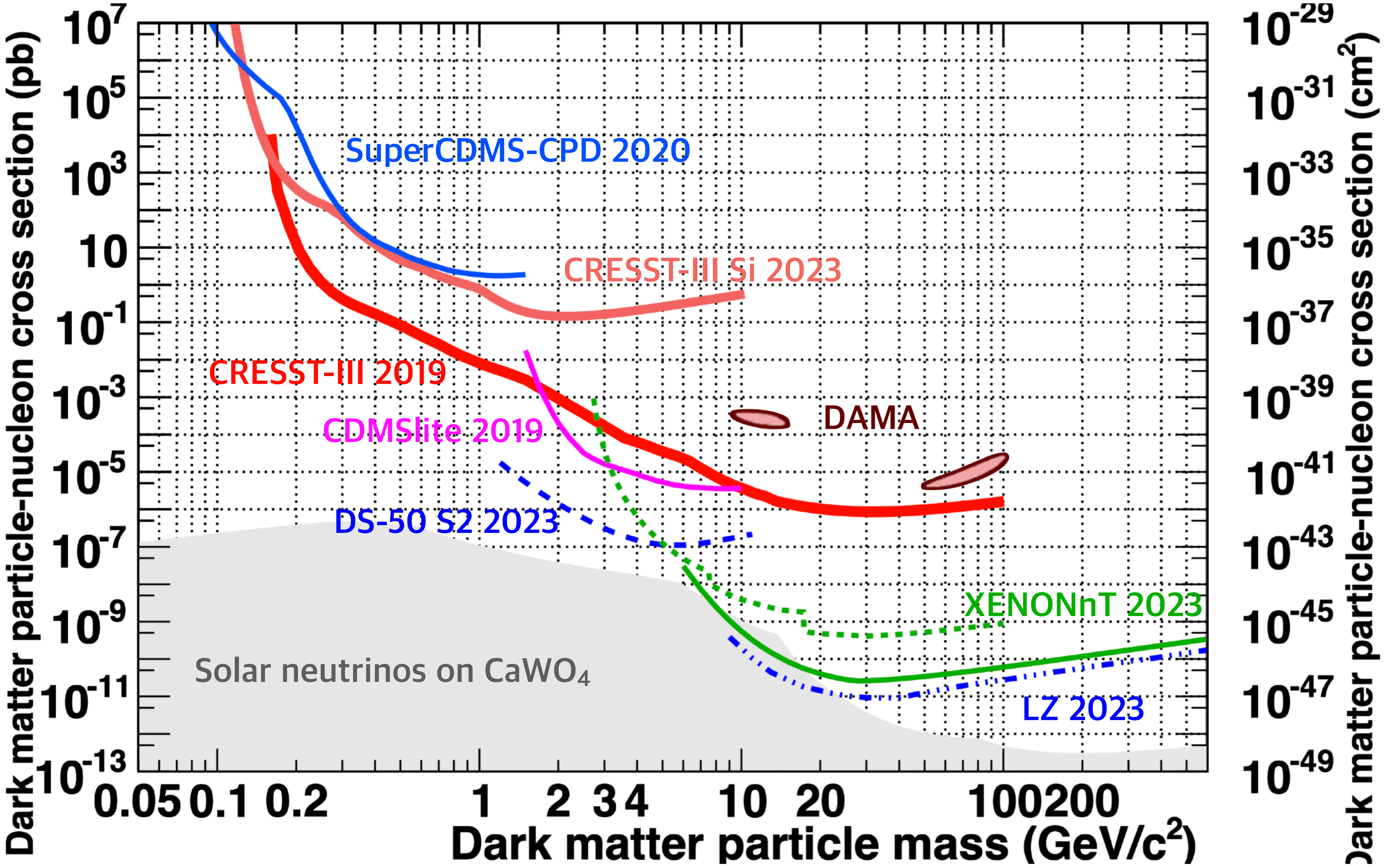


Modified from CRESST Coll., Phys. Rev. D 107, 122003 (2023)

Detector energy threshold 10 eV

Constraining DM properties

THE LOWER, THE BETTER



CRESST leader in sub-GeV DM searches

> detector low-energy threshold

Credits to Anna Bertolini
Thanks!

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Supernovae: cosmic fireworks

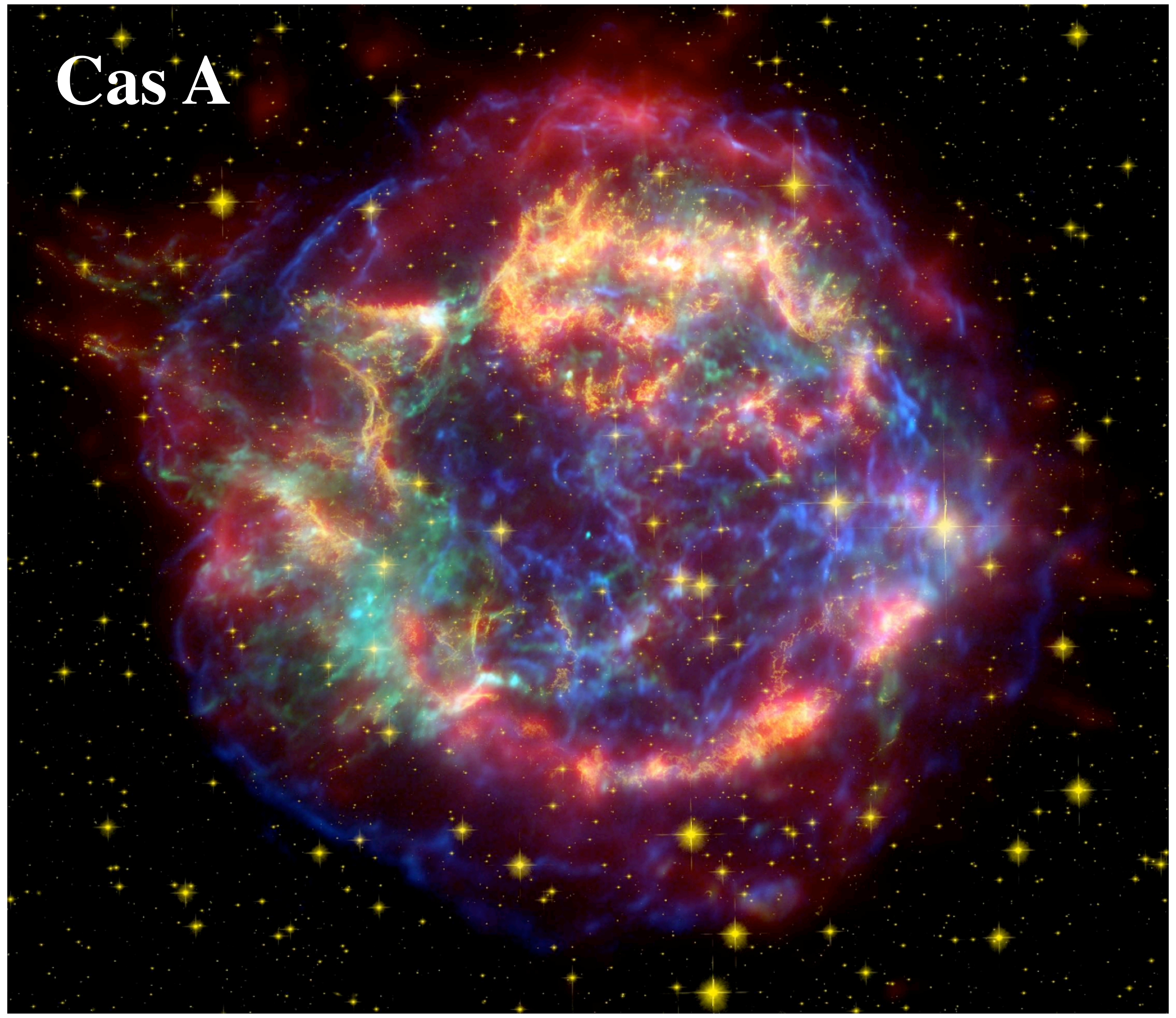
SETTING THE STAGE

Supernovae (SN): high-energy **explosions of massive stars**

Almost total star binding energy converted into **all flavor-neutrinos** but also **GW** and **EM** radiation

Neutrinos: direct **probes** and **messengers** of SNe hidden dynamics

Rare event: **1 observation** with underground instrumentation (1987)

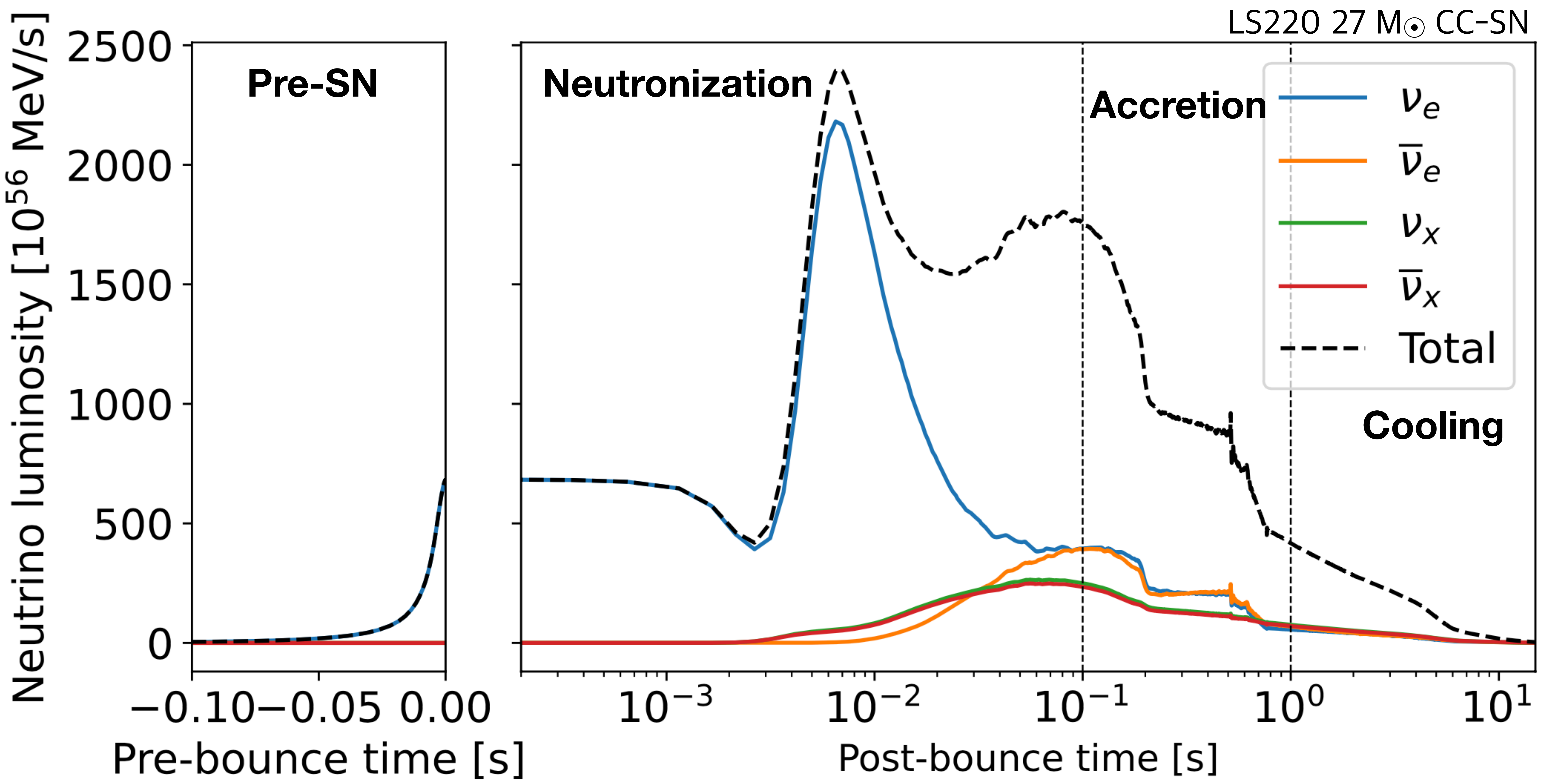


Wikipedia - Combination of images from Hubble, Spitzer e Chandra

Neutrinos are emitted at all times

Unique neutrino signature

Neutrino transport simulation of a Core-Collapse SN



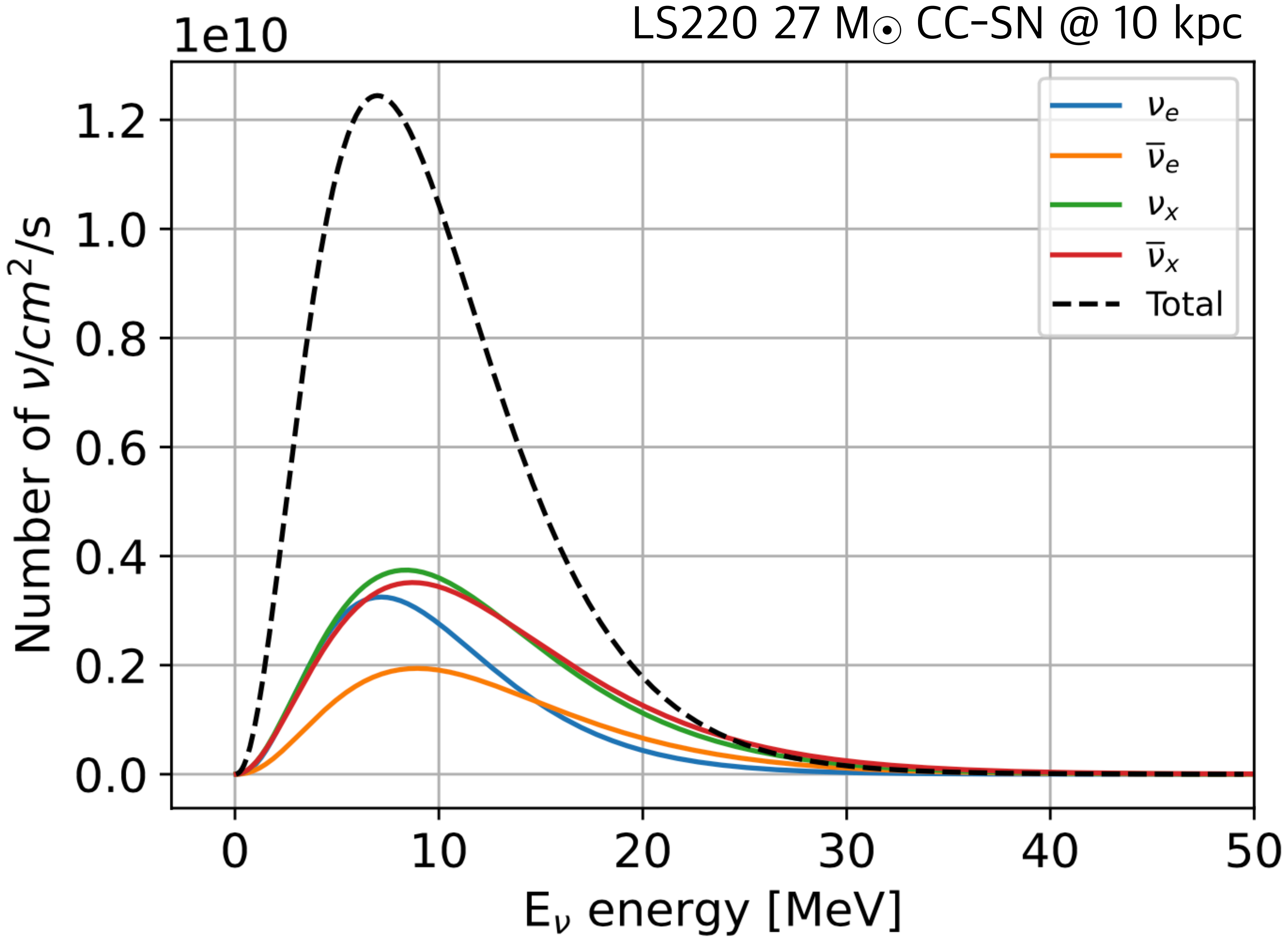
A. Mirizzi et al., Riv. Nuovo Cim.39, 1 (2016)

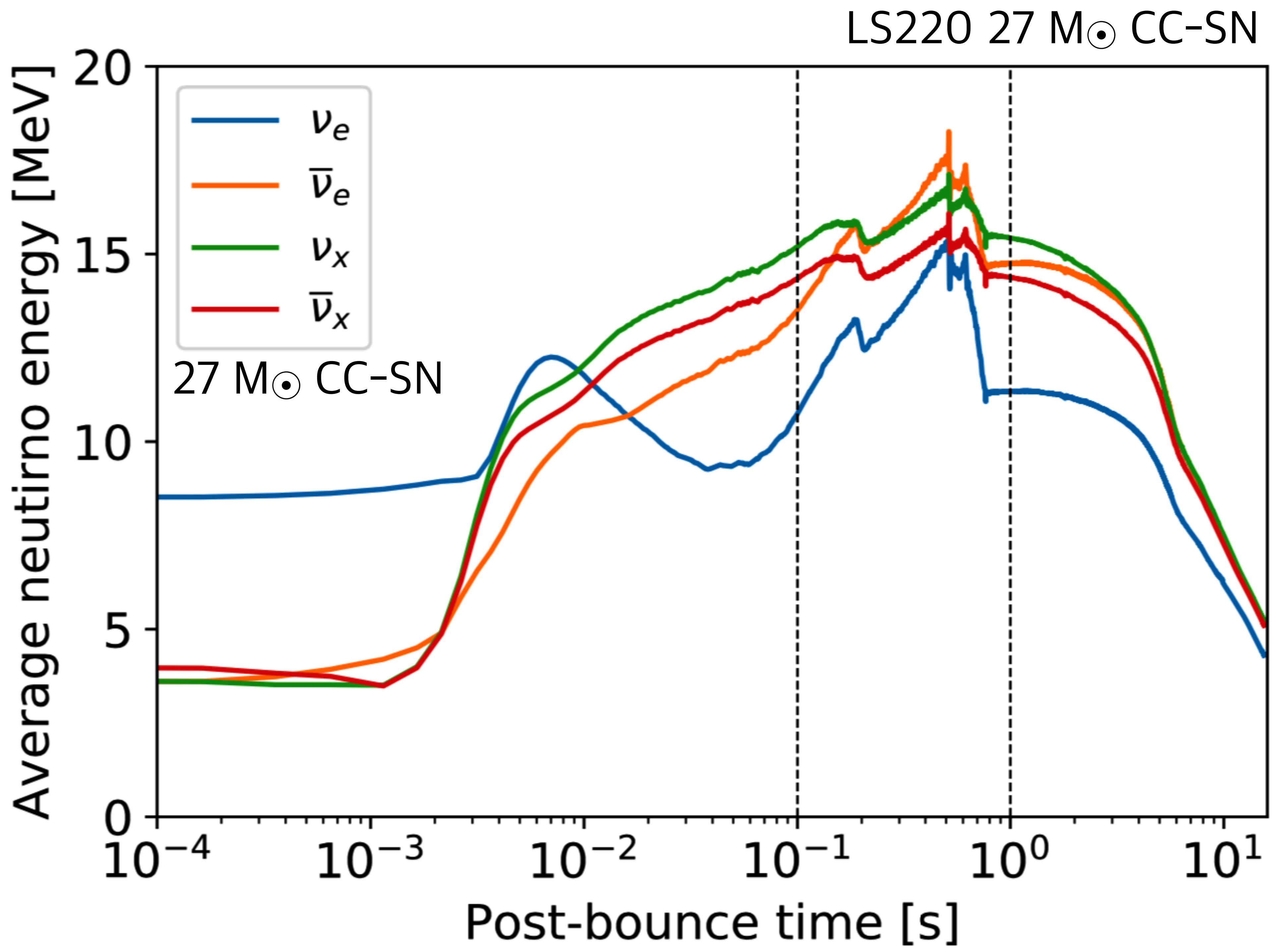
Nota Bene: neutrino flavor oscillations not included

MPA Supernova Archive:
https://wwwmpa.mpa-garching.mpg.de/ccsnarchive

Supernova Neutrino signal

What is the average neutrino energy?





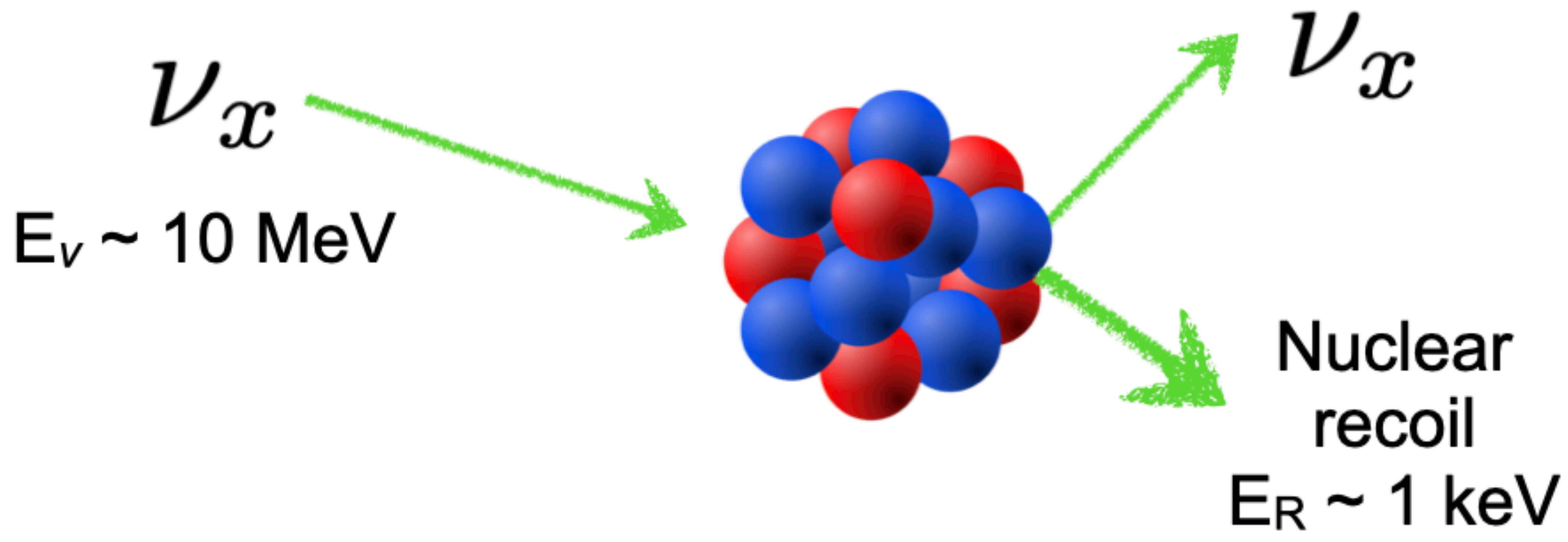
ν_x is the most **intense** component of the flux

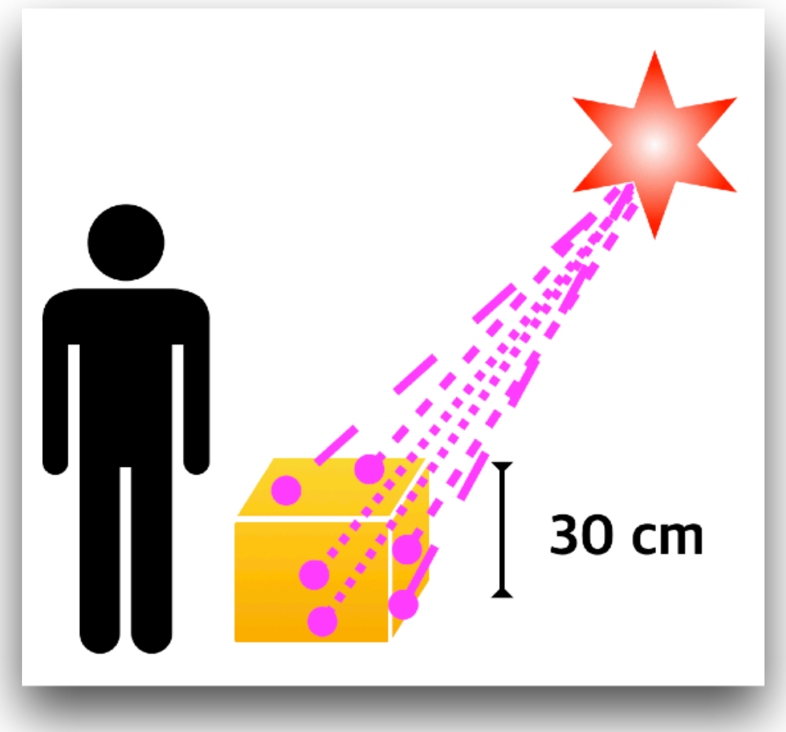
ν_x is the most **energetic** component of the flux

Current SN neutrino detectors are mostly sensitive to anti-ν_e/ν_e

All neutrino flavors are detected

Coherent neutrino-nucleus scattering





> Equally sensitive to all ν-flavors

> High interaction cross-section

$$\sigma_{CE\nu NS} = \frac{G_F^2}{4\pi} F^2(q^2)\, E_\nu^2\, Q_W^2$$

cross-section

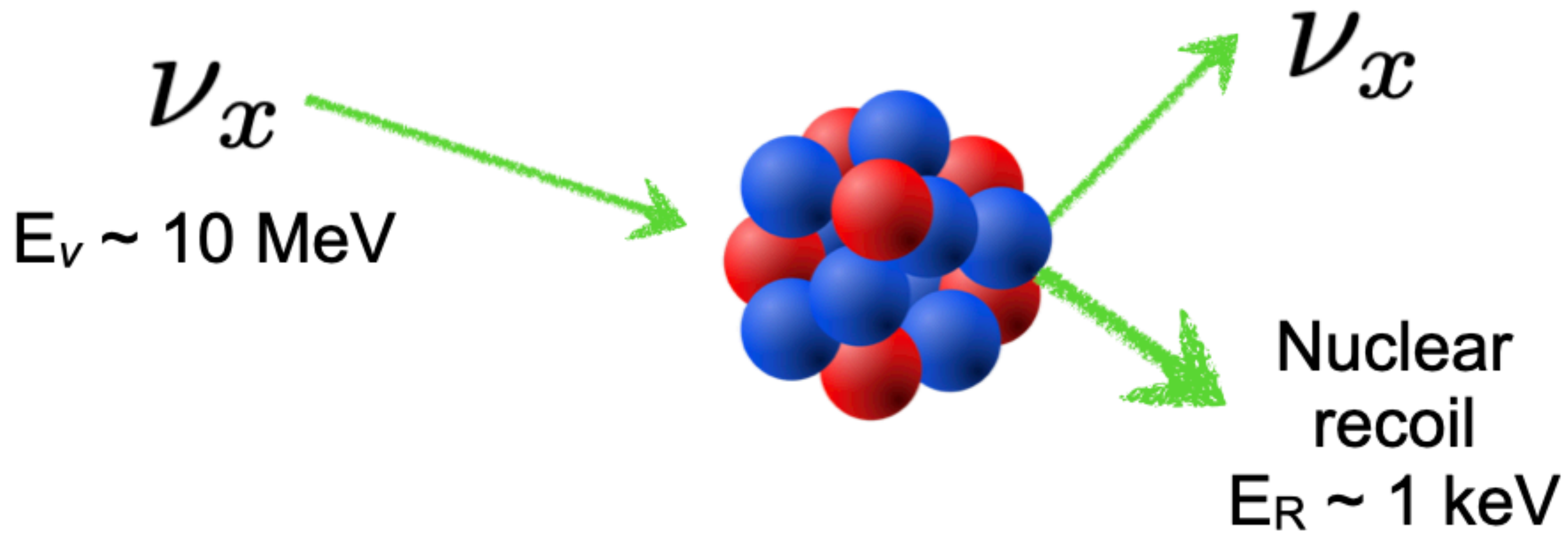
Nuclear Form factor

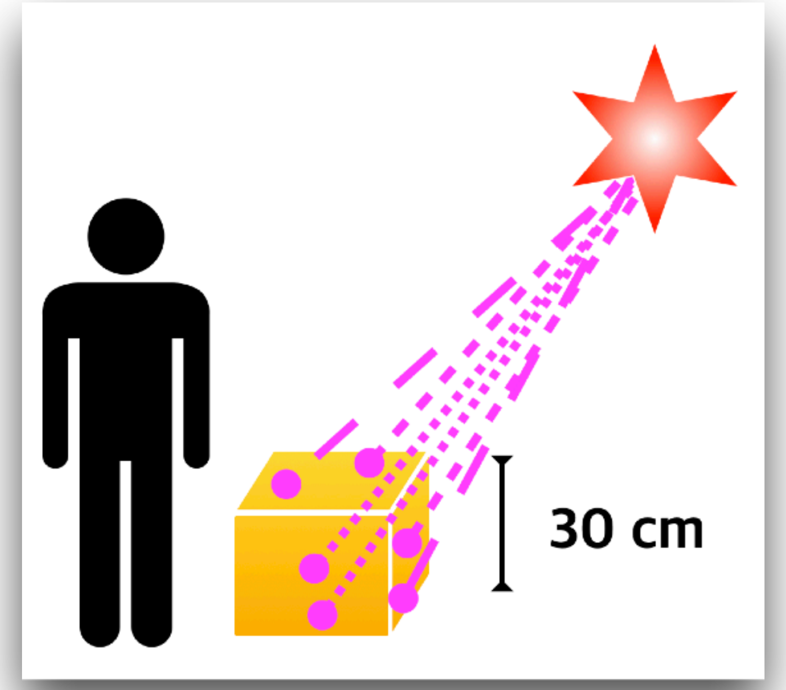
Neutrino energy

Weak nuclear charge

All neutrino flavors are detected

Coherent neutrino-nucleus scattering





> Equally sensitive to all ν-flavors

> High interaction cross-section

$$Q_W = N - Z\overbrace{(1 - 4\sin^2\theta_W)}^{\sim 5\%}$$

$$\sigma_{CE\nu NS}{}^{*} = \frac{G_F^2}{4\pi} F^2(q^2)\, E_\nu^2\, Q_W^2$$

cross-section

Nuclear Form factor

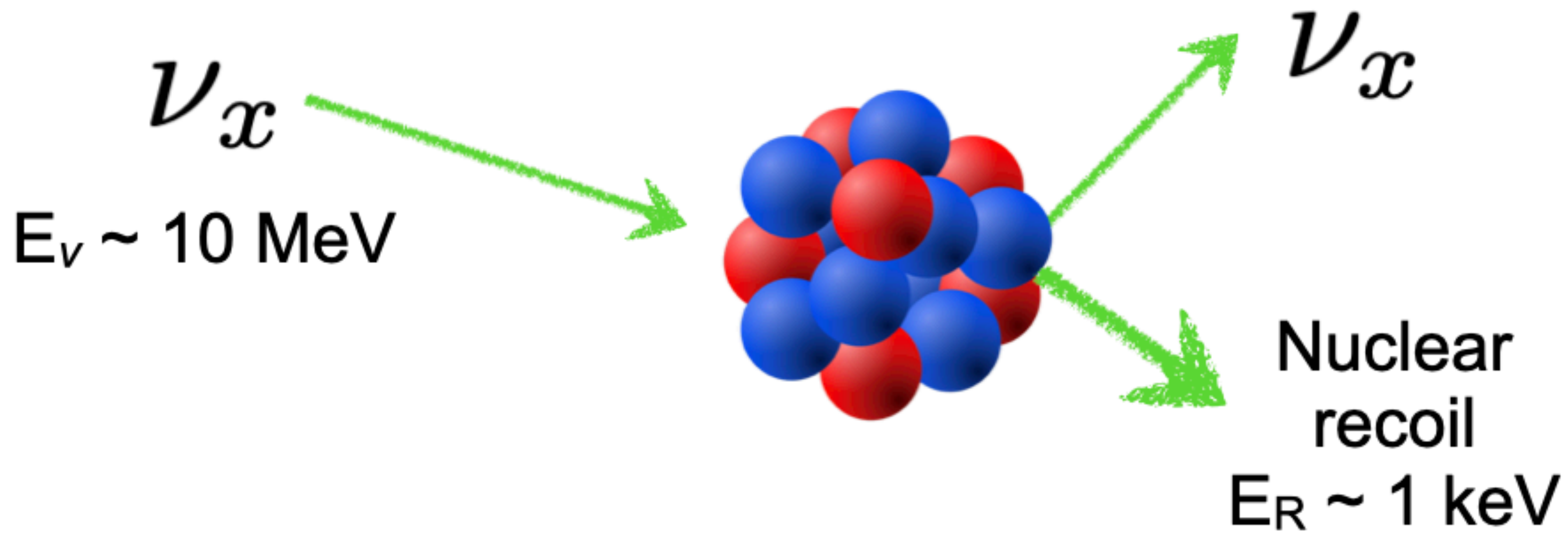
Neutrino energy

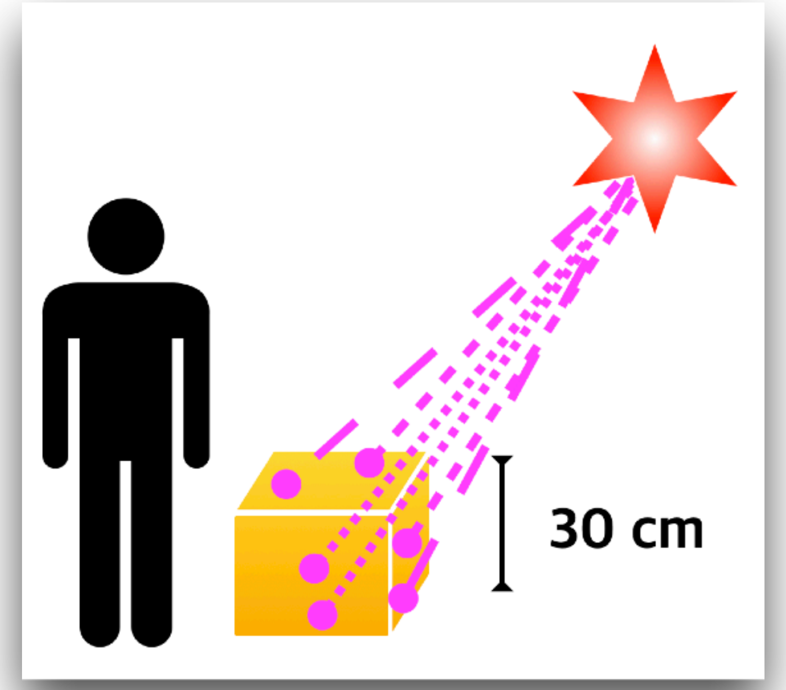
Weak nuclear charge

* Spin 0 interaction

All neutrino flavors are detected

Coherent neutrino-nucleus scattering





> Equally sensitive to all ν-flavors

> High interaction cross-section

$$\sigma_{CE\nu NS} \propto N^2$$

cross-section

Neutron number

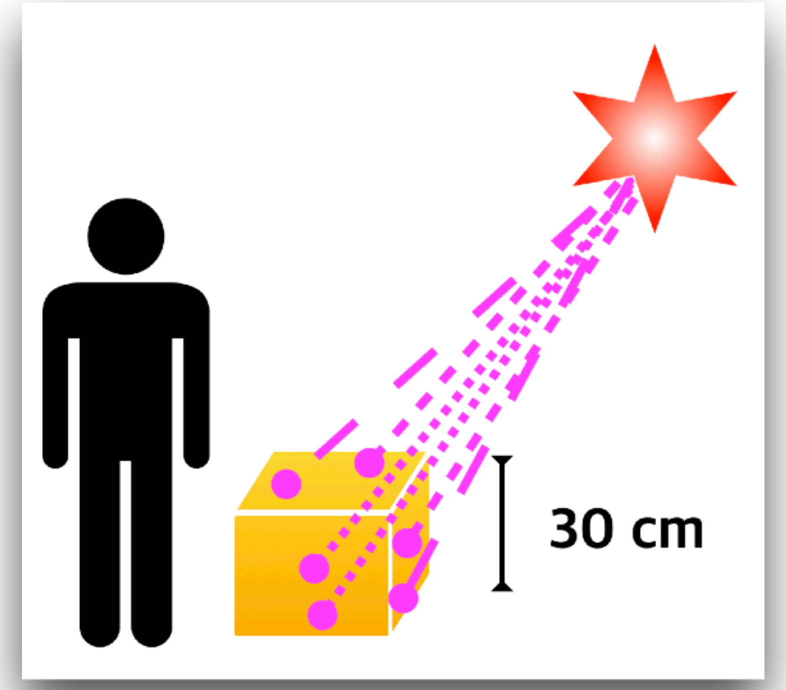
All neutrino flavors are detected

Coherent neutrino-nucleus scattering

$$\sigma_{CE\nu NS} \propto N^2$$

cross-section

Neutron number



Pb ideal target

Highest neutron number

Highest nuclear stability

All neutrino flavors are detected

Coherent neutrino-nucleus scattering

$$\sigma_{CE\nu NS} \propto N^2$$

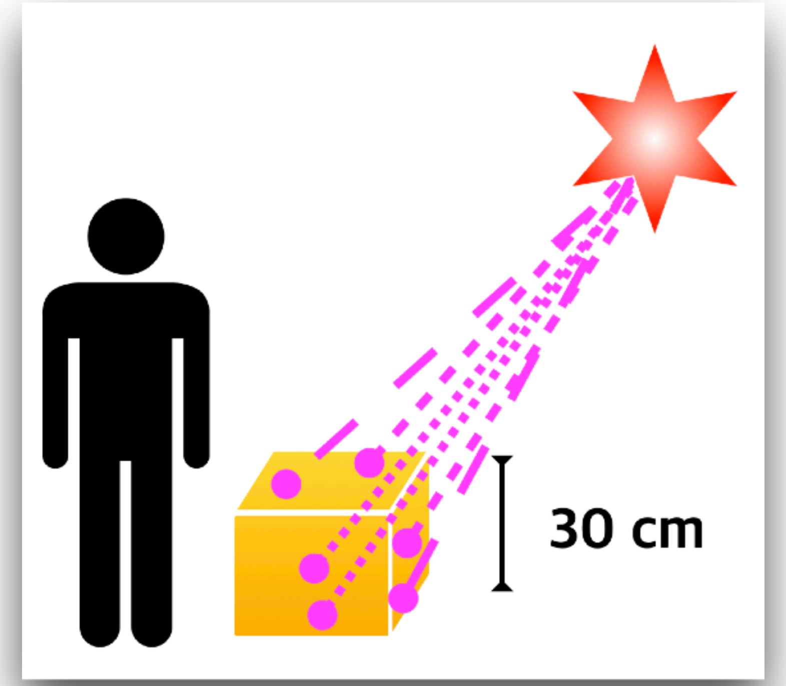
cross-section

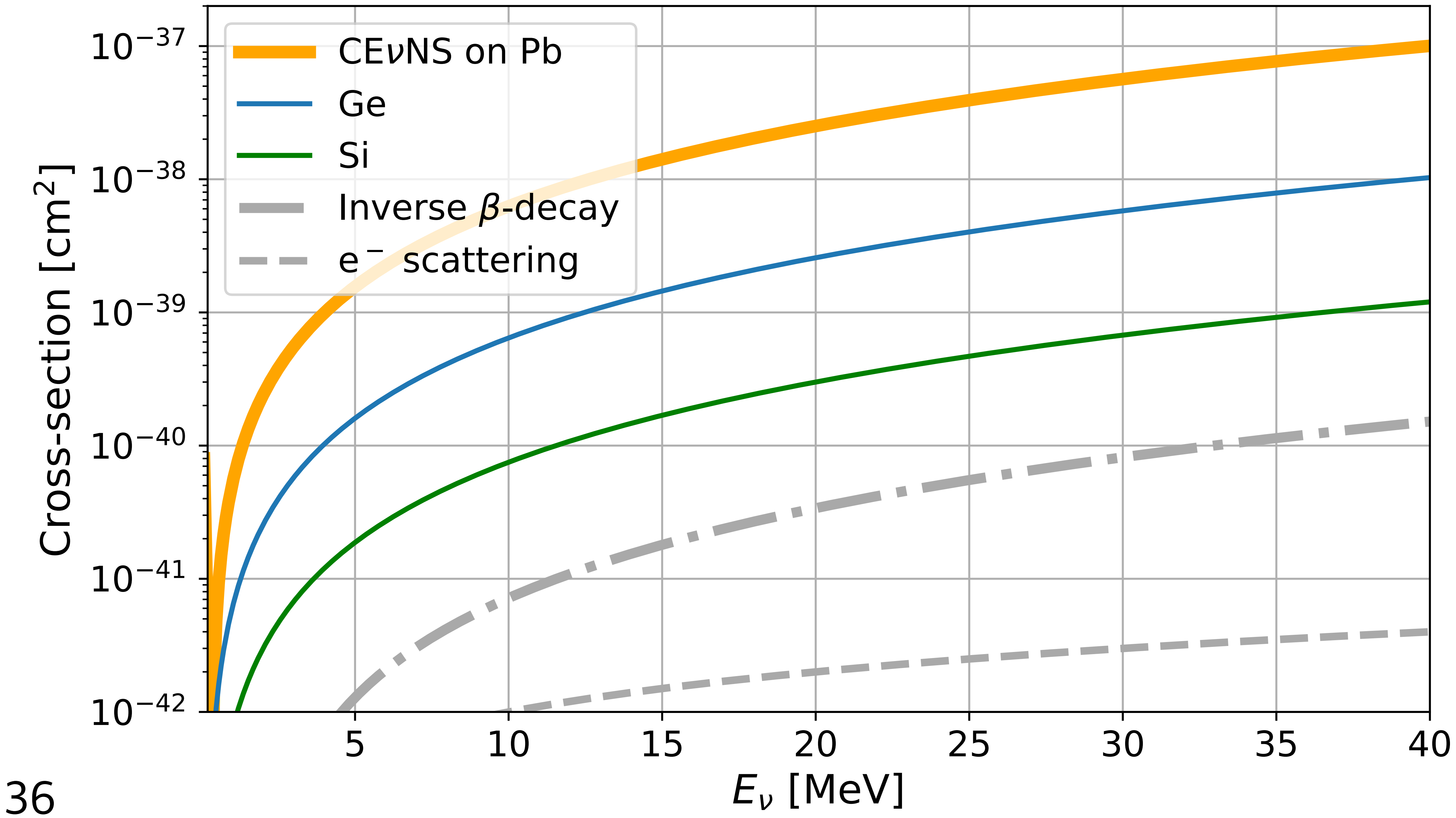
Neutron number

<u>Pb ideal target</u>

Highest neutron number

Highest nuclear stability





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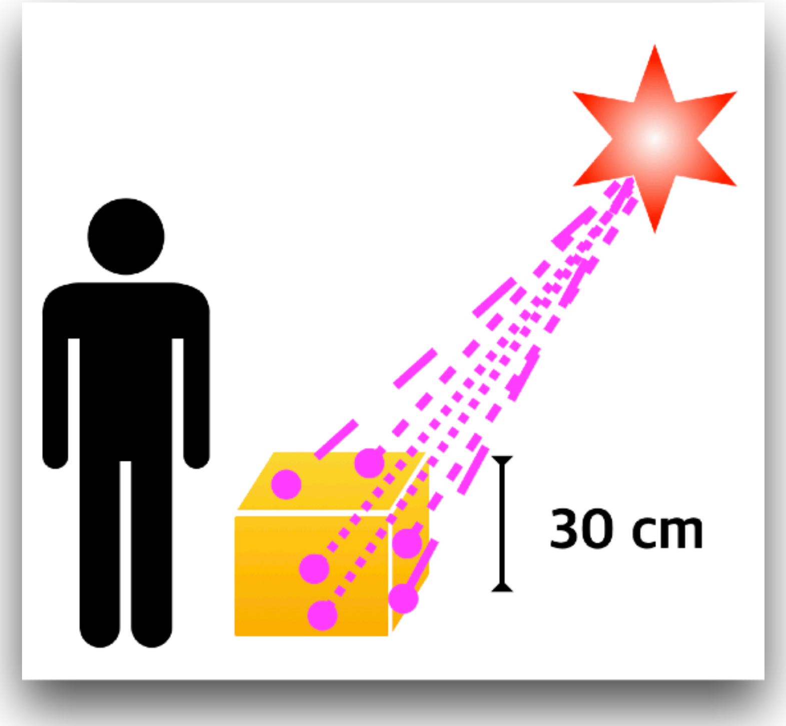
cross-section

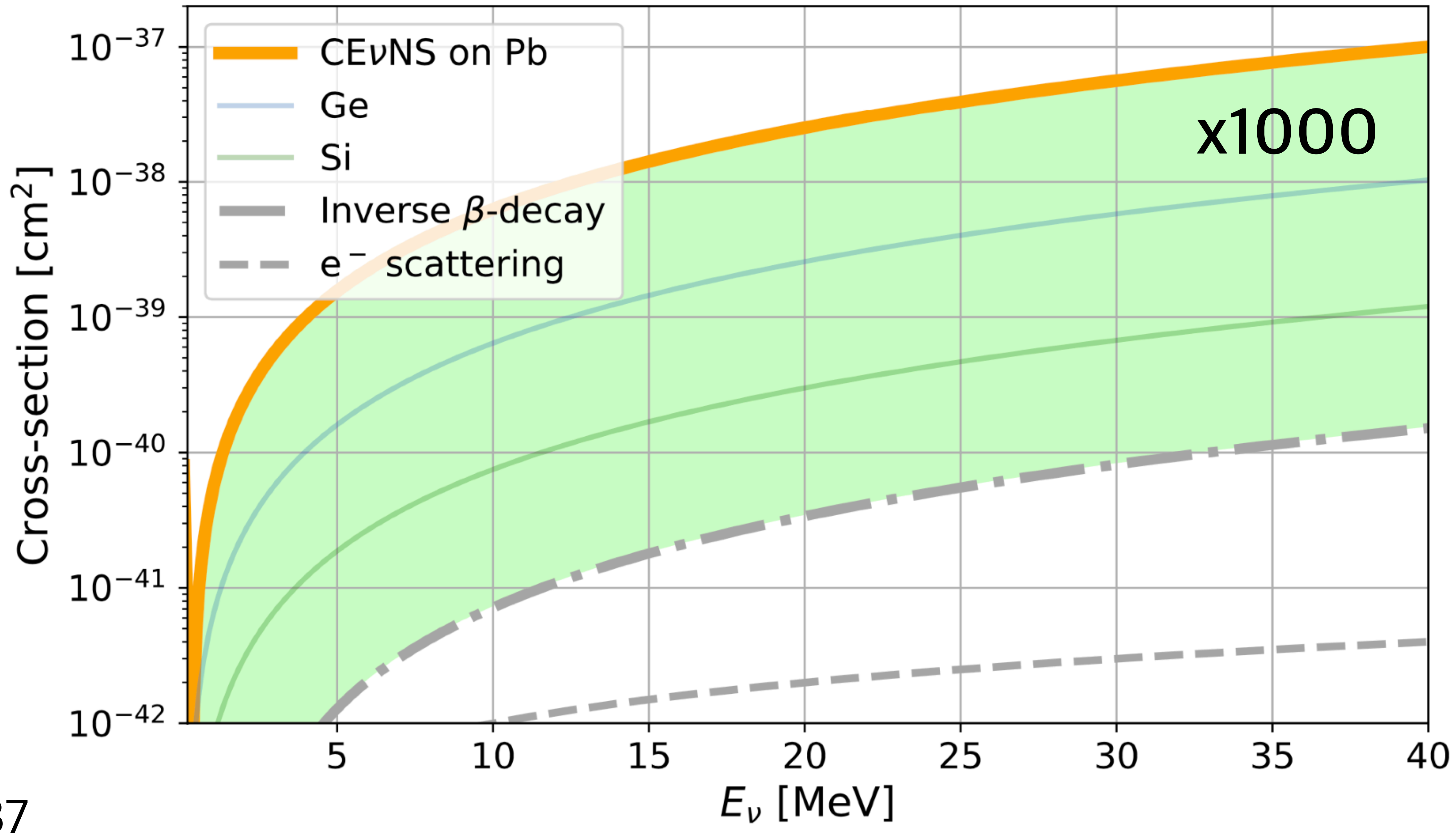
Neutron number

Pb ideal target

Highest neutron number

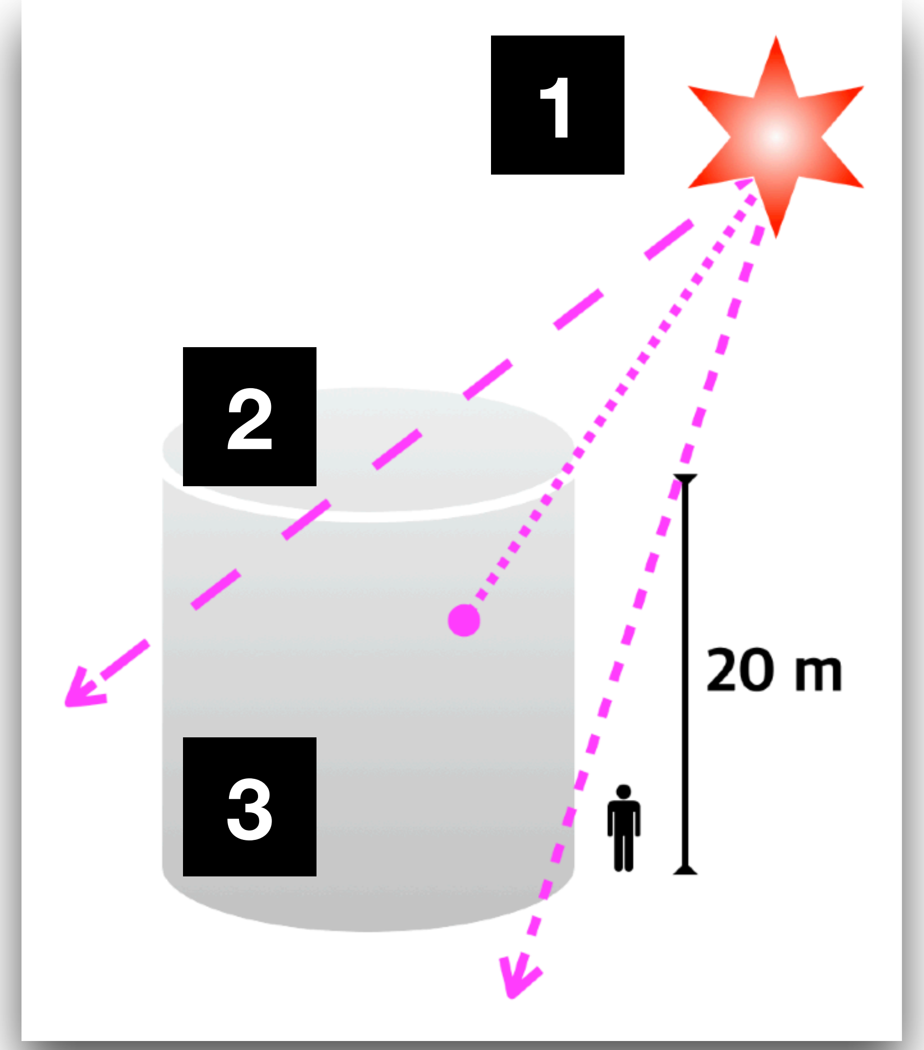
Highest nuclear stability





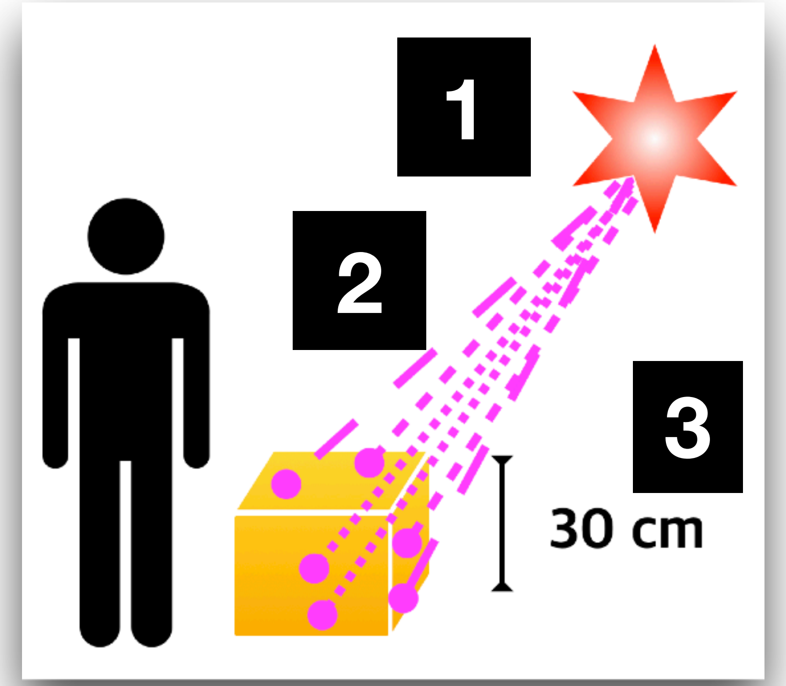
All neutrino flavors are detected

Coherent neutrino-nucleus scattering



Status quo:

1. detection of ~1/6 SN flux
2. small cross-section
3. large volume detectors

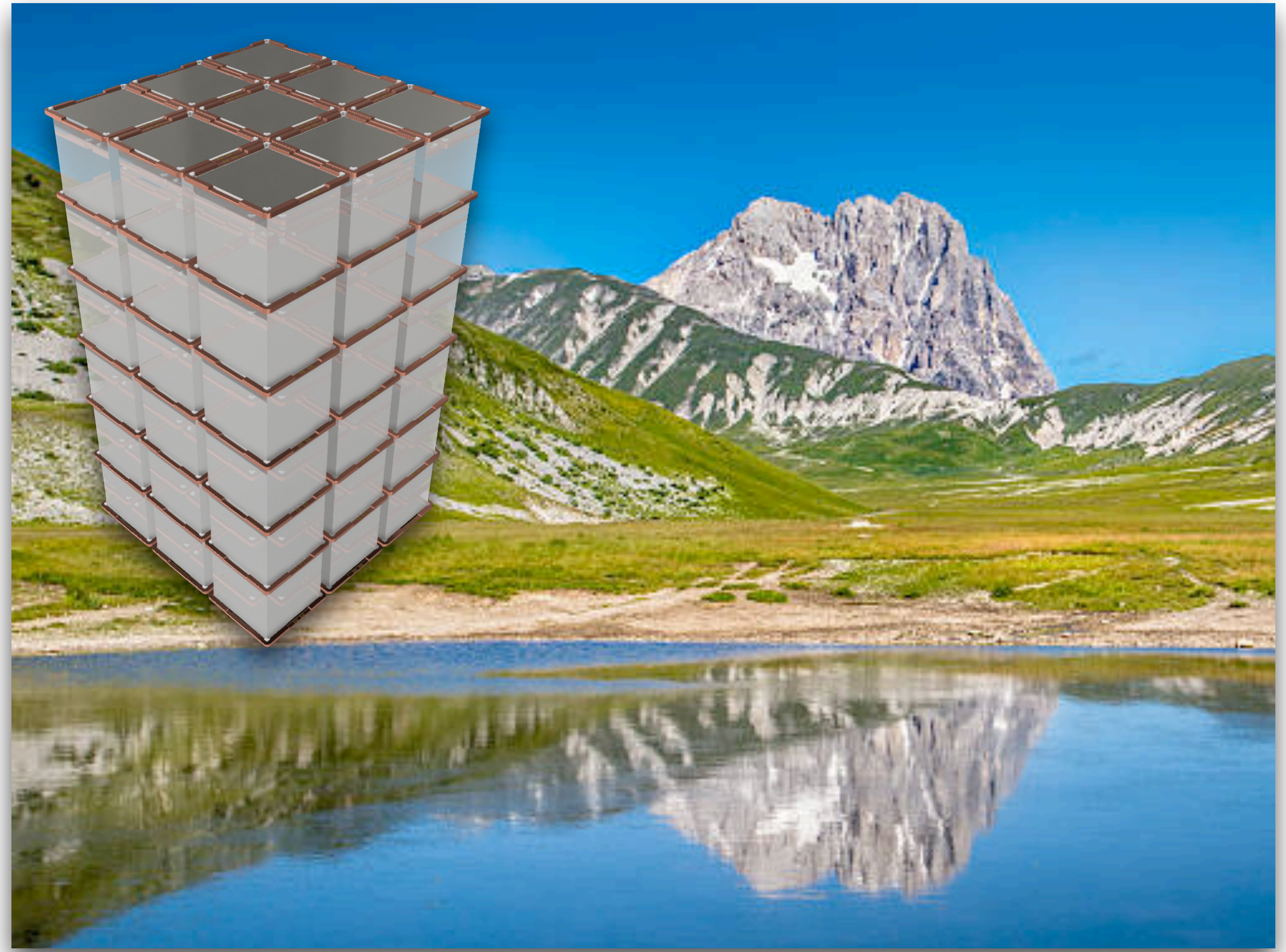


Opportunities:

1. detection of full SN ν flux
2. highest cross-section
3. cm-scale ν telescope

RES-NOVA experiment

"New thing" - a new way to look at neutrinos



- Ultra-low background cryo detectors
- Low-energy neutrino observatory
- International Group of Interest (40+ members)

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

INFN

GRAN SASSO SCIENCE INSTITUTE
CENTER FOR ADVANCED STUDIES INFN

SICCAS Since 1928

European Research Council
Established by the European Commission

RES-NOVA gives unique insights into SNe

Innovative experimental approach

RES-NOVA

Detection channel
Coherent neutrino-nucleus scattering

Technology
Cryogenic detectors

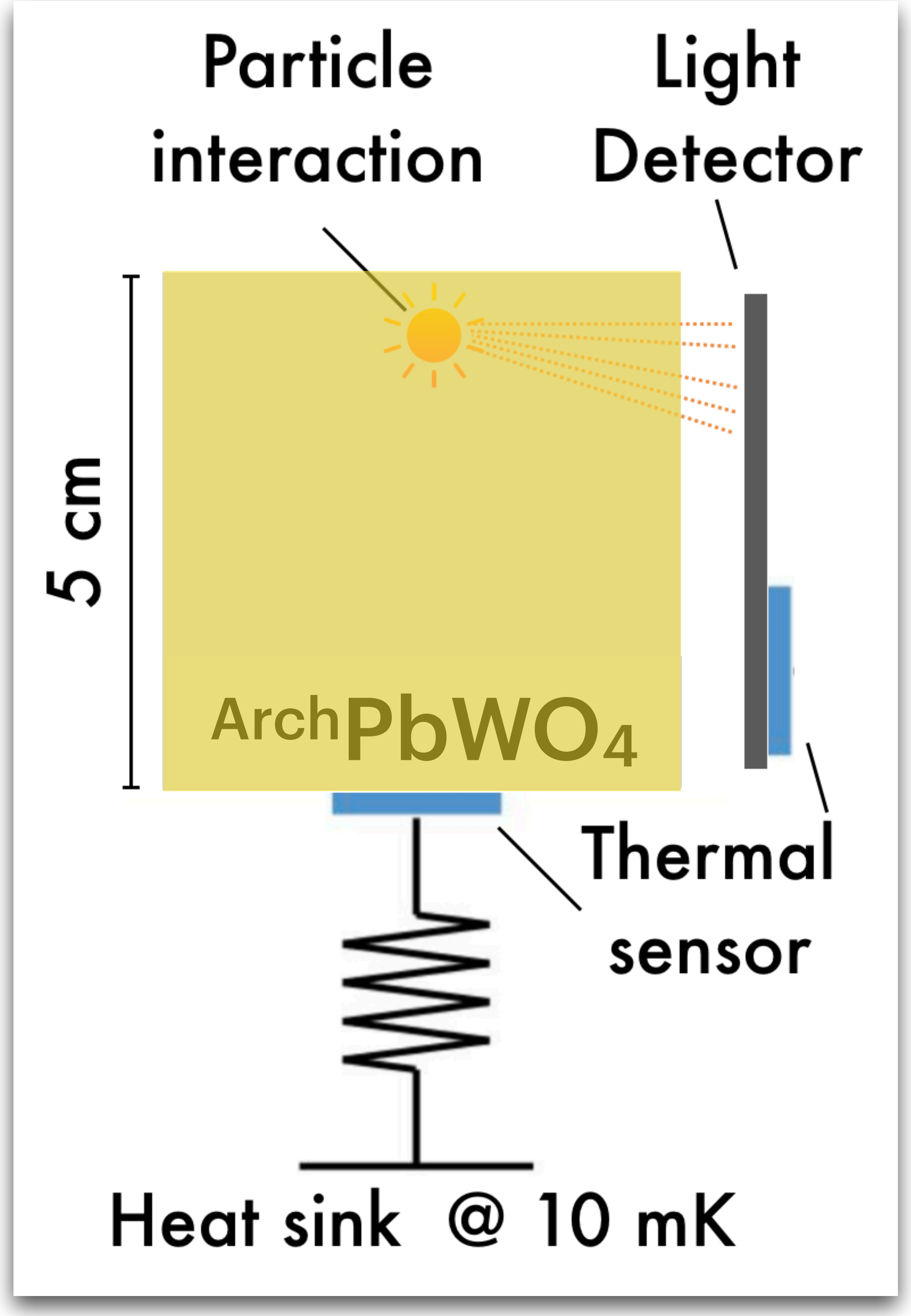
Target material
$PbWO_4$ from archaeological-Pb

European Research Council
Established by the European Commission

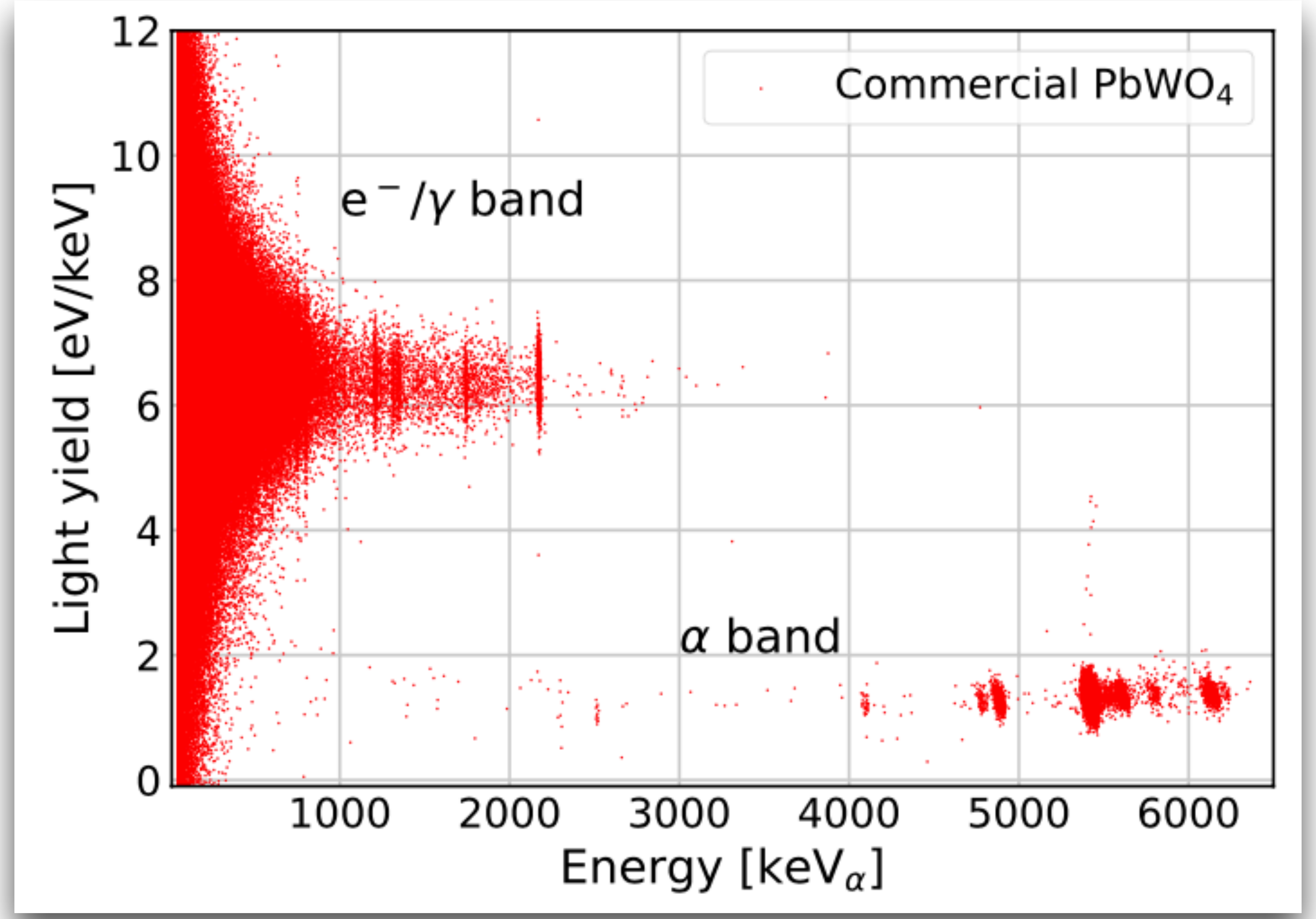
RES-NOVA detector technology

Advanced Cryogenic Detectors

Cryogenic calorimeters made from Pb



Cryogenic measurement of commercial $PbWO_4$



J.W. Beeman, **LP** et al., Eur. Phys. J. A 49, 50 (2013)

RES-NOVA gives unique insights into SNe

Innovative experimental approach

RES-NOVA

Detection channel
Coherent neutrino-nucleus scattering

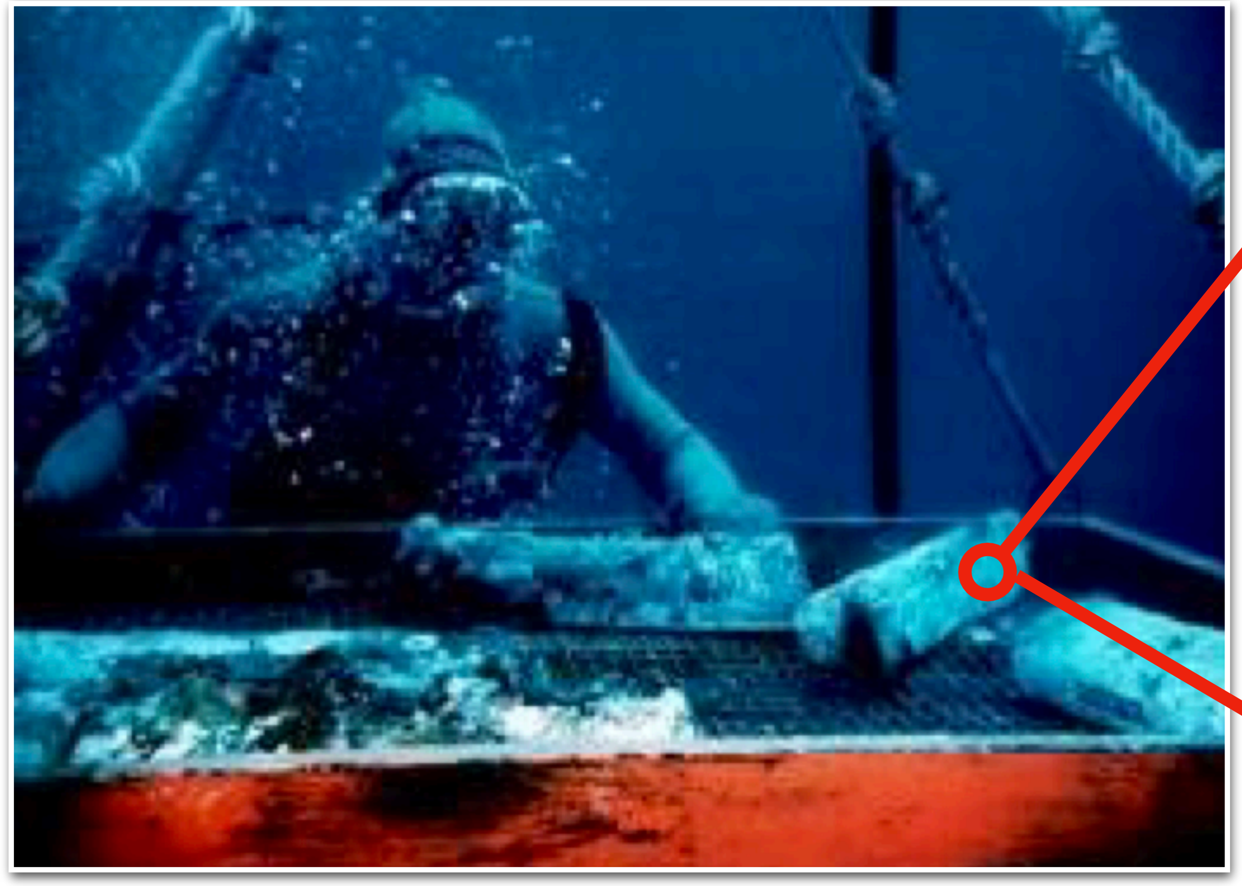
Technology
Cryogenic detectors

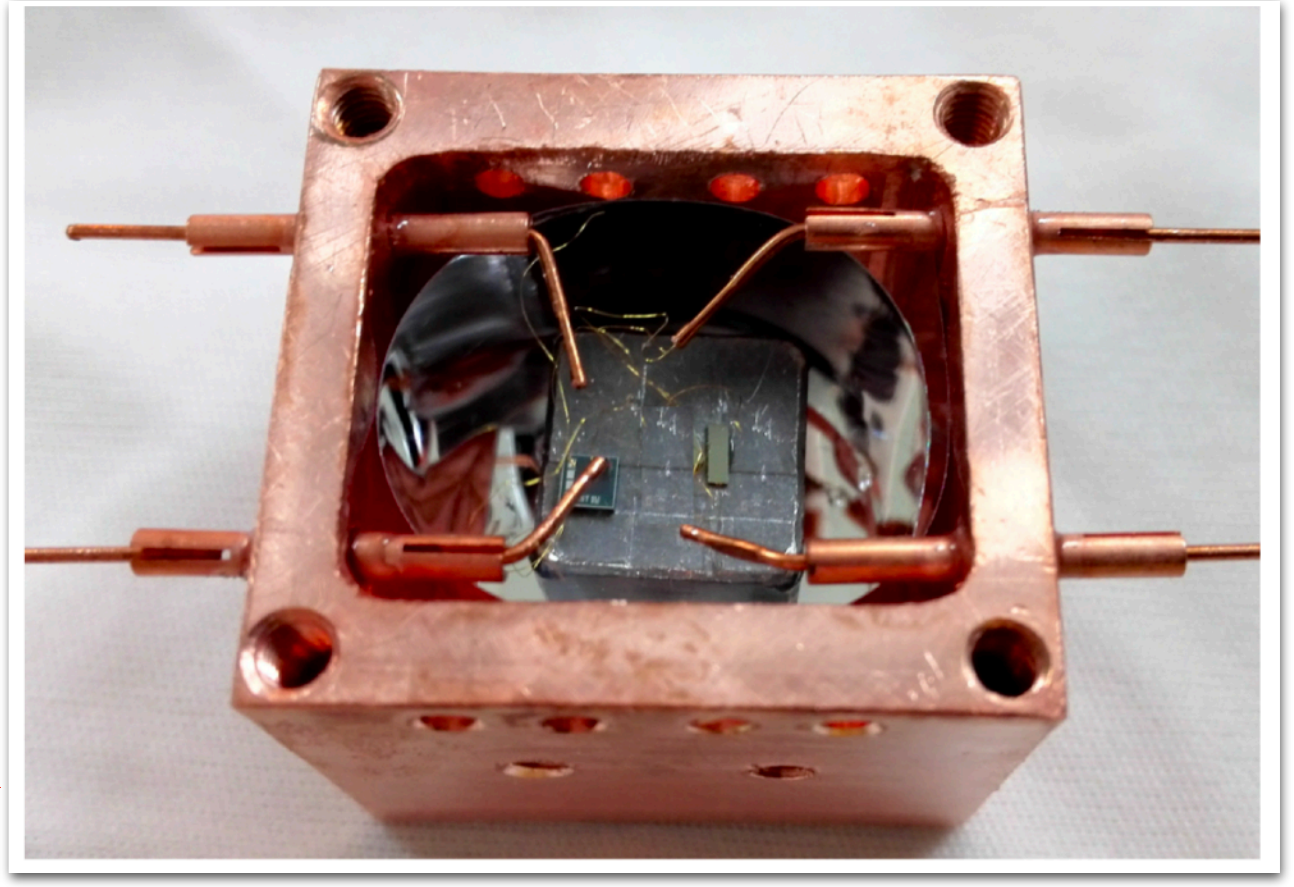
Target material
$PbWO_4$ from archaeological-Pb

erc
European Research Council
Established by the European Commission

Cryogenic detectors built from Archaeological Pb

taken from N. Nosengo (2010)





Archaeological Roman Pb:

★ from underwater shipwreck

★ 2000 years old

Archaeo-Pb cryogenic detector

High radiopurity: < 1 mBq/kg

x10^4 better than commercial low-background Pb

Several tons of ^{Arch}Pb available

L. Pattavina et al., Eur. Phys. J. A 55, 127 (2019)

RES-NOVA gives unique insights into SNe

Innovative experimental approach

RES-NOVA

Detection channel
Coherent neutrino-nucleus scattering

Technology
Cryogenic detectors

Target material
$PbWO_4$ from archaeological-Pb

erc
European Research Council
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RES-NOVA gives unique insights into SNe

Innovative experimental approach

→

Detection channel
Coherent neutrino-nucleus scattering

Technology
Cryogenic detectors

Target material
$PbWO_4$ from archaeological-Pb

What can we learn?

Galactic SN neutrino signal:

Water Cherenkov (SuperK): 0.2 ev./m^3

Liquid Scintillator (SNO+): 0.4 ev./m^3

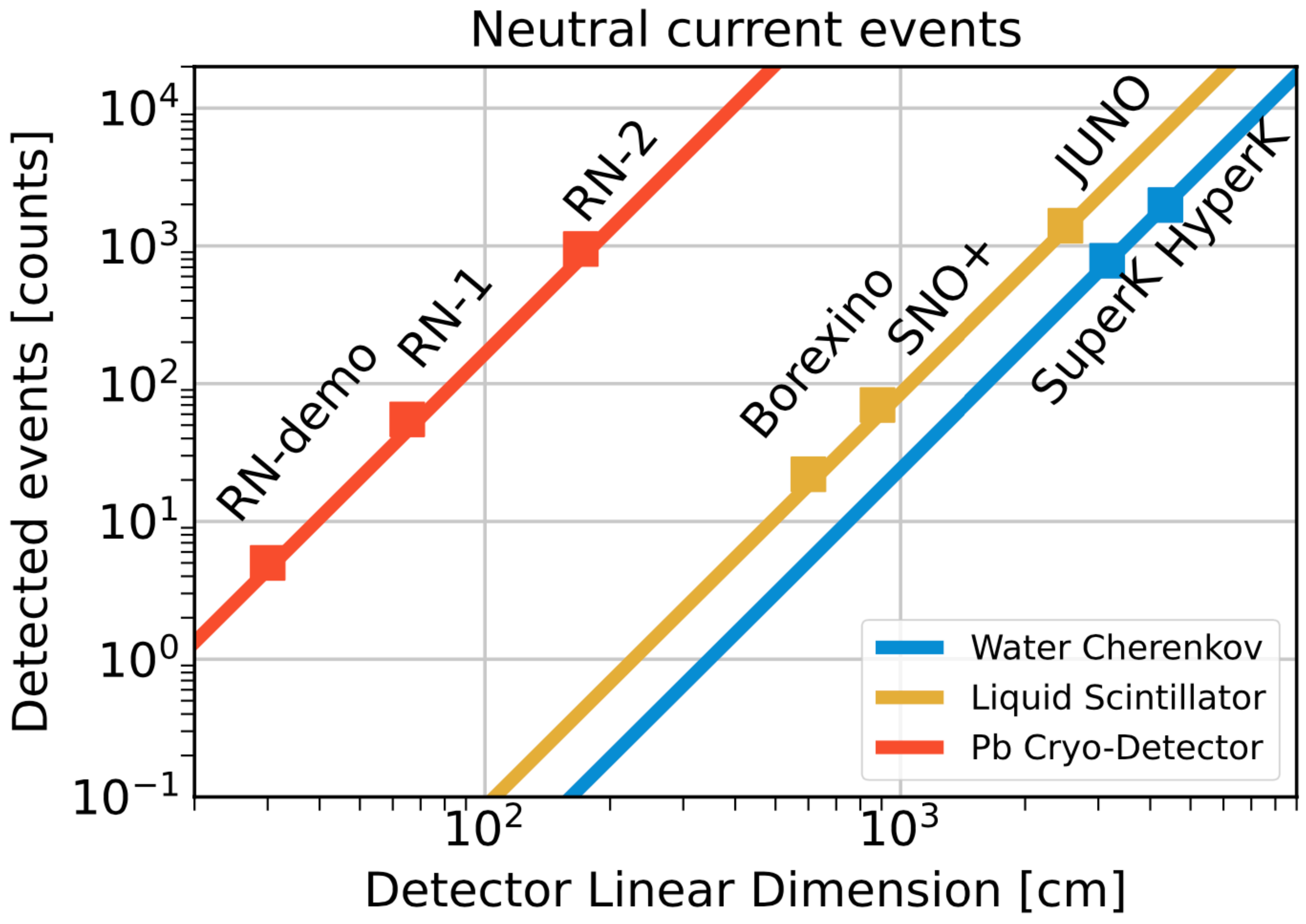
<u>RES-NOVA: ~200 ev./m^3</u>

- Core-collapse physics studies
- Characterization of SN remnants
- Neutrino mass properties
- Multi-messenger Astronomy

European Research Council
Established by the European Commission

Neutrino observatory at the cm-scale

an array of $PbWO_4$ crystals

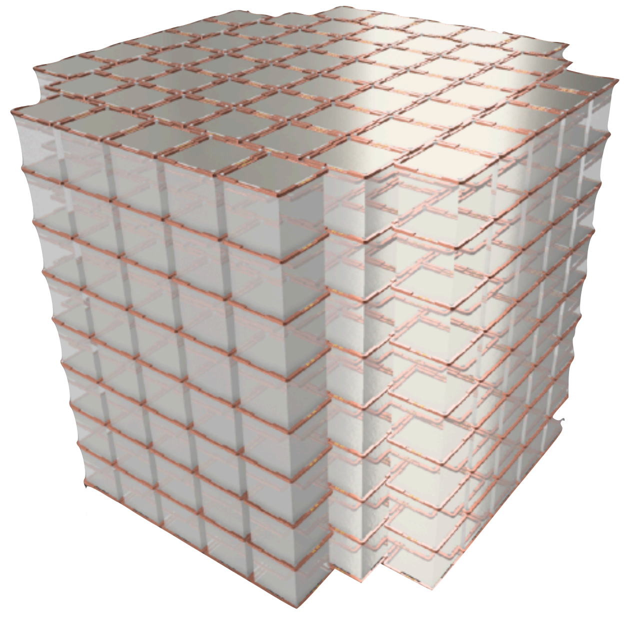


Size: Threshold: SN @ 10 kpc:

RN-demo @ LNGS
$(30\ \text{cm})^3$
1 keV
~10 counts

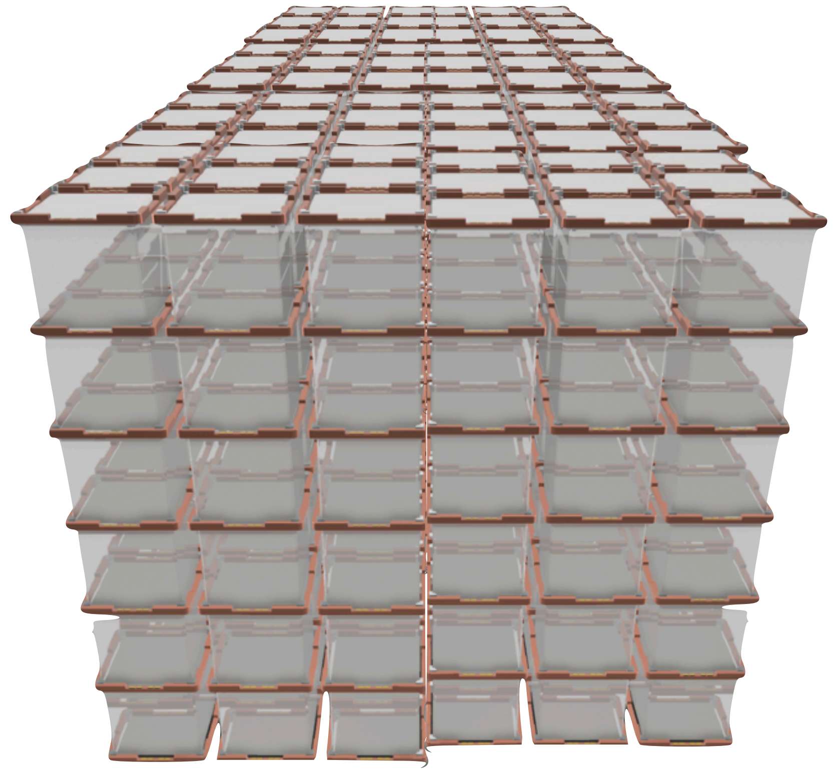
Size: Threshold: SN @ 10 kpc:

RN-1
$(60\ \text{cm})^3$
1 keV
~50 counts



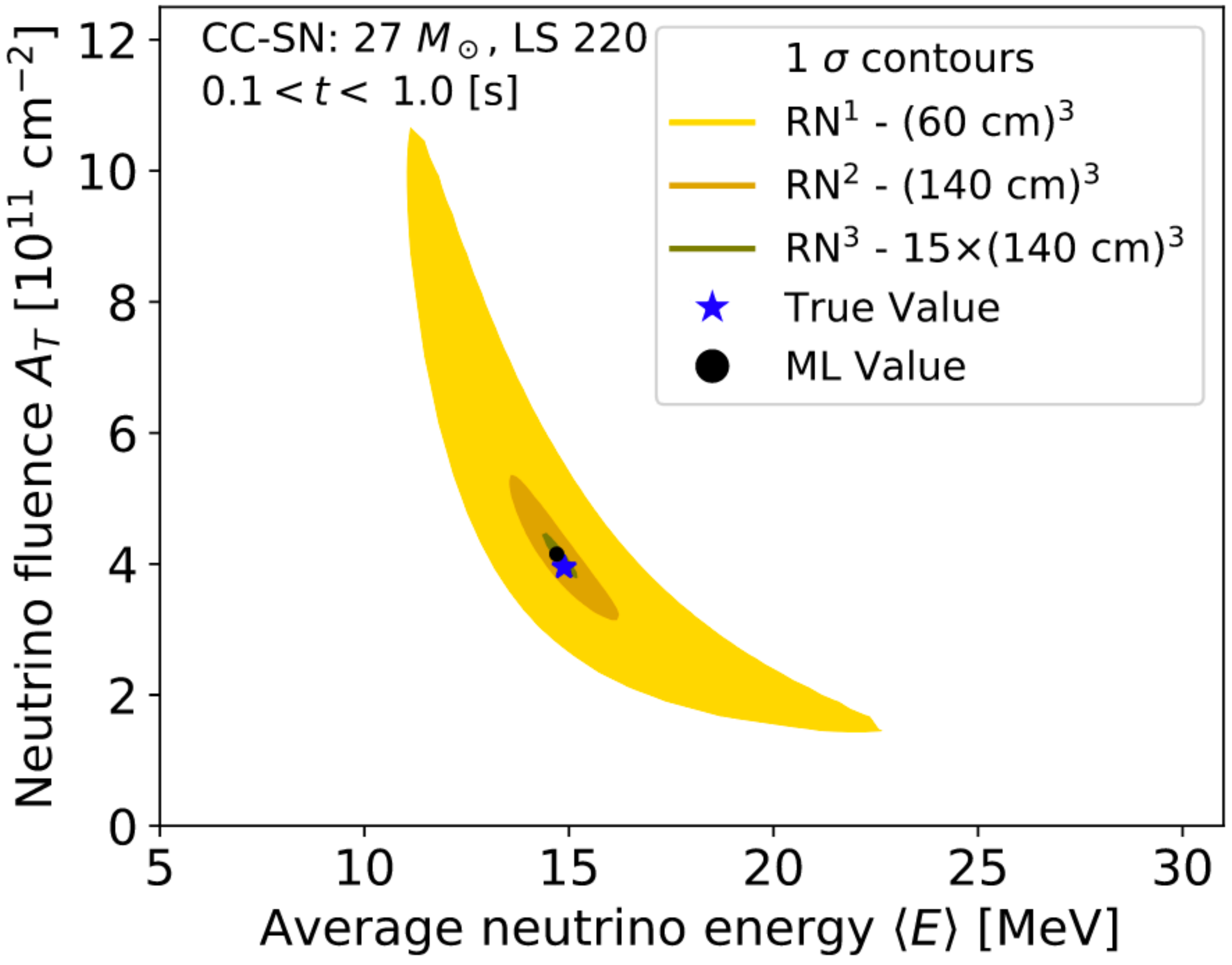
Size: Threshold: SN @ 10 kpc:

RN-2
$(140\ \text{cm})^3$
1 keV
~900 counts



SN energy reconstruction in RES-NOVA

Reconstruction of A_T and <E> by likelihood analysis



$$\mathcal{E}_{\rm tot} = 4\pi d^2 A_T \langle E \rangle$$

Neutrino fluence

Average neutrino energy

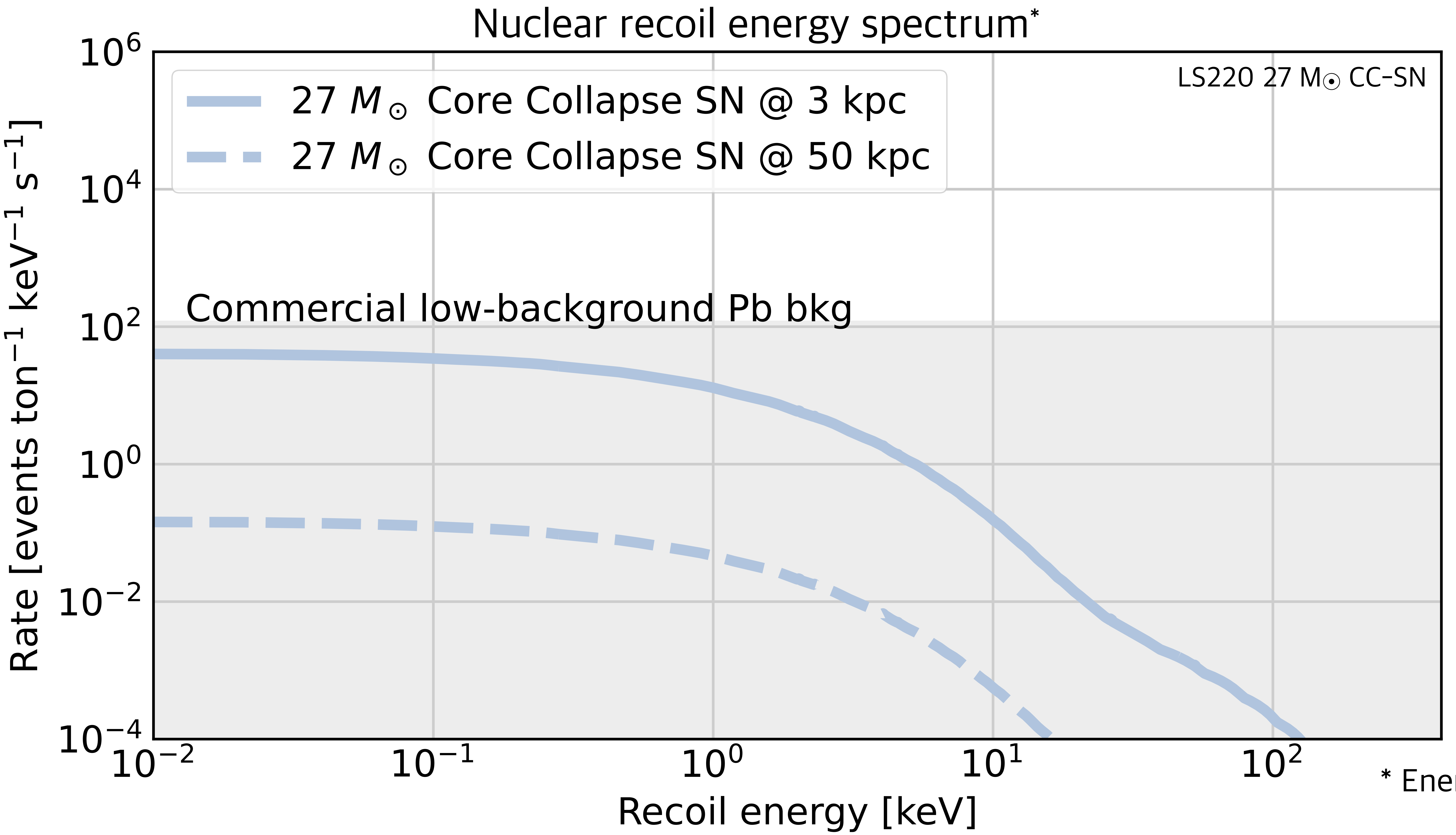
Precision in total SN energy reconstruction

ν_x/anti-ν_x		ν_e/anti-ν_e	
RN-I	30%		
RN-2	8%	SK-Gd (IBD)	25%
RN-3	4%		

L. Pattavina et al., Phys. Rev. D 102, 063001 (2020)

A. Gallo Rosso et al., JCAP 04 (2018) 040

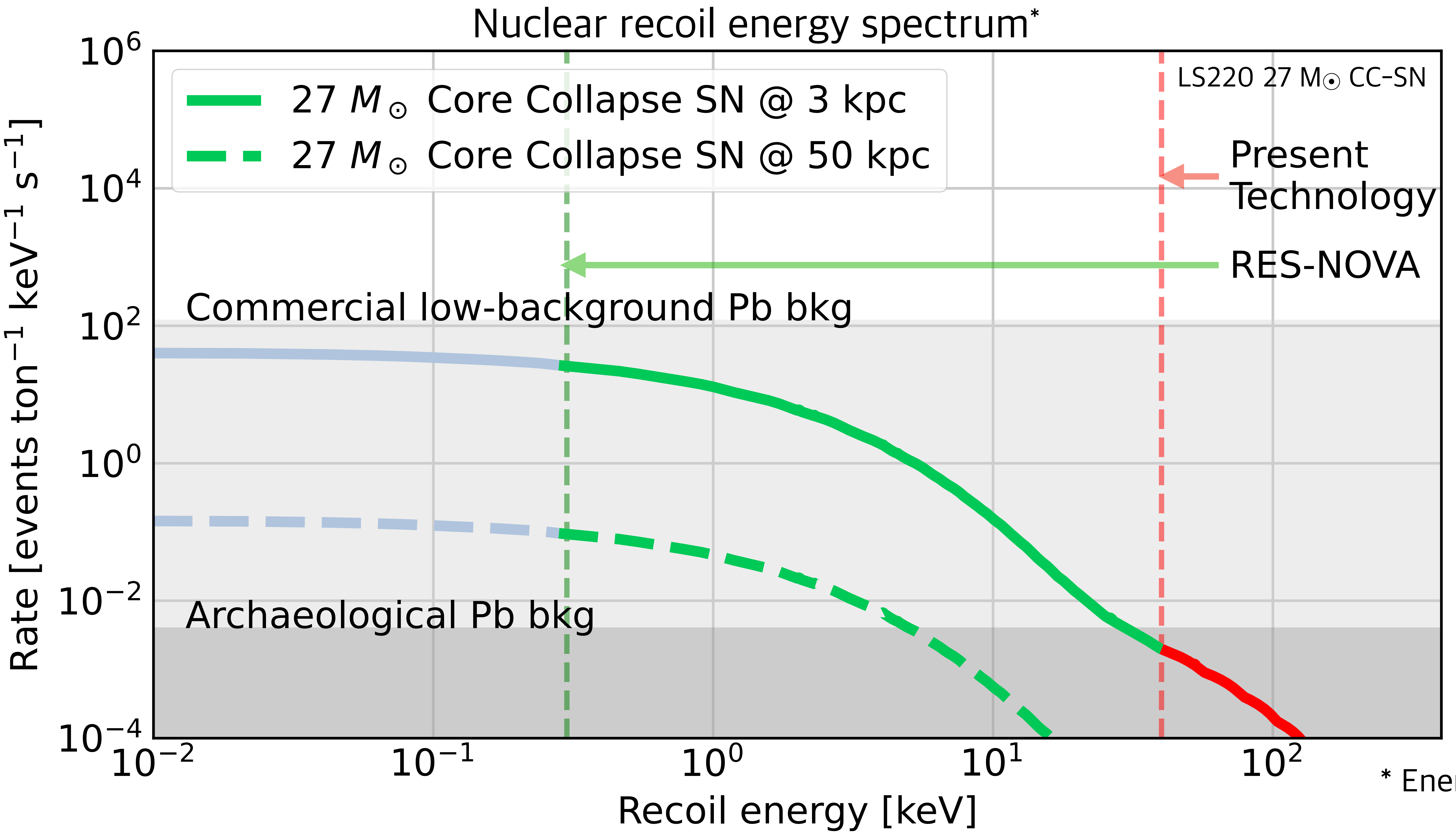
RES-NOVA detects SN neutrinos



* Energy resolution 0.2 keV

L. Pattavina et al., *Phys. Rev. D* 102, 063001 (2020)

RES-NOVA detects SN neutrinos



* Energy resolution 0.2 keV

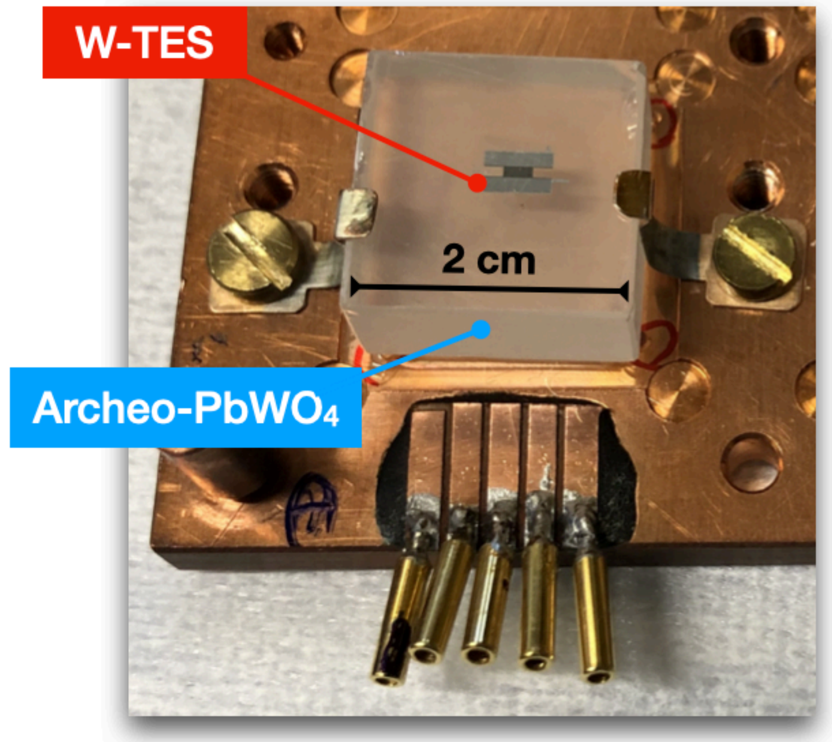
L. Pattavina et al., *Phys. Rev. D* 102, 063001 (2020)

RES-NOVA Group of Interest, *Eur. Phys. J. C* 82, 692 (2022)

N. Ferreiro, L. Pattavina et al., J. Low Temp. Phys. 11, 184 (2022)

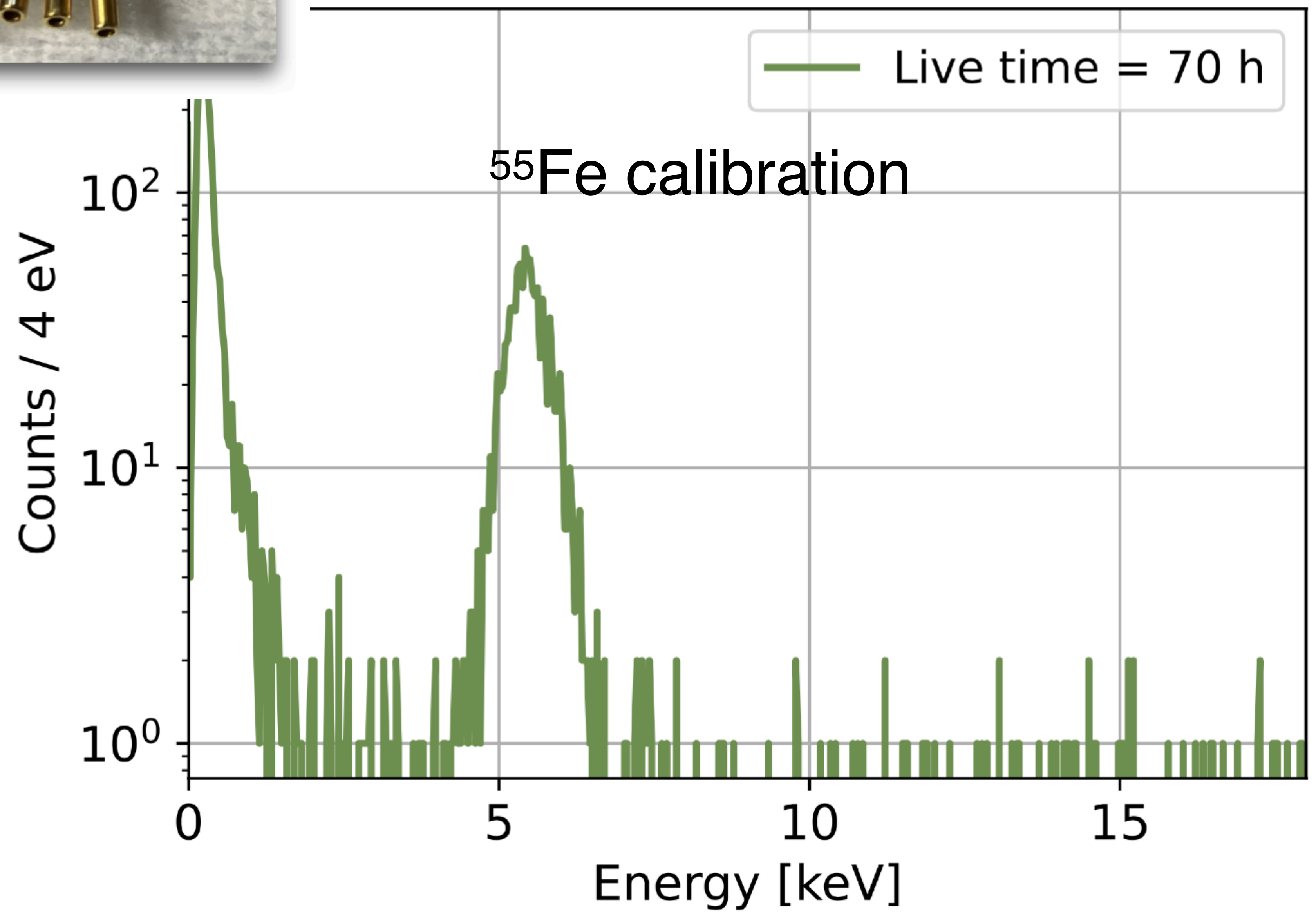
RES-NOVA PROOFS OF PRINCIPLE

ACHIEVEMENT OF LOW THRESHOLD AND LOW BACKGROUND



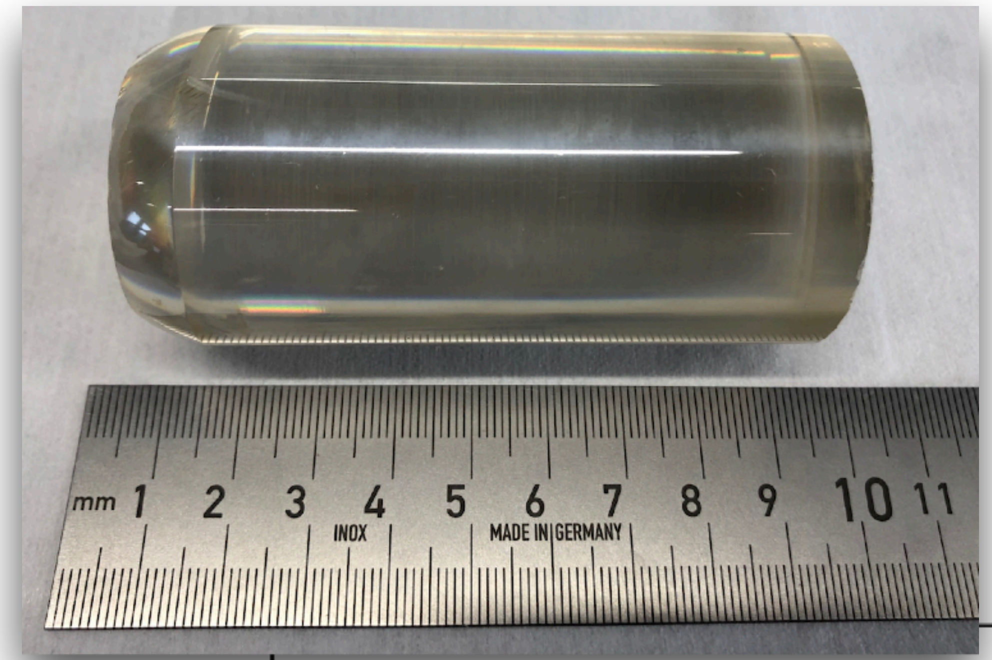
N. Ferreiro Iachellini et al.,
J. Low Temp. Phys. 11, 184 (2022)

TOTAL ENERGY SPECTRUM



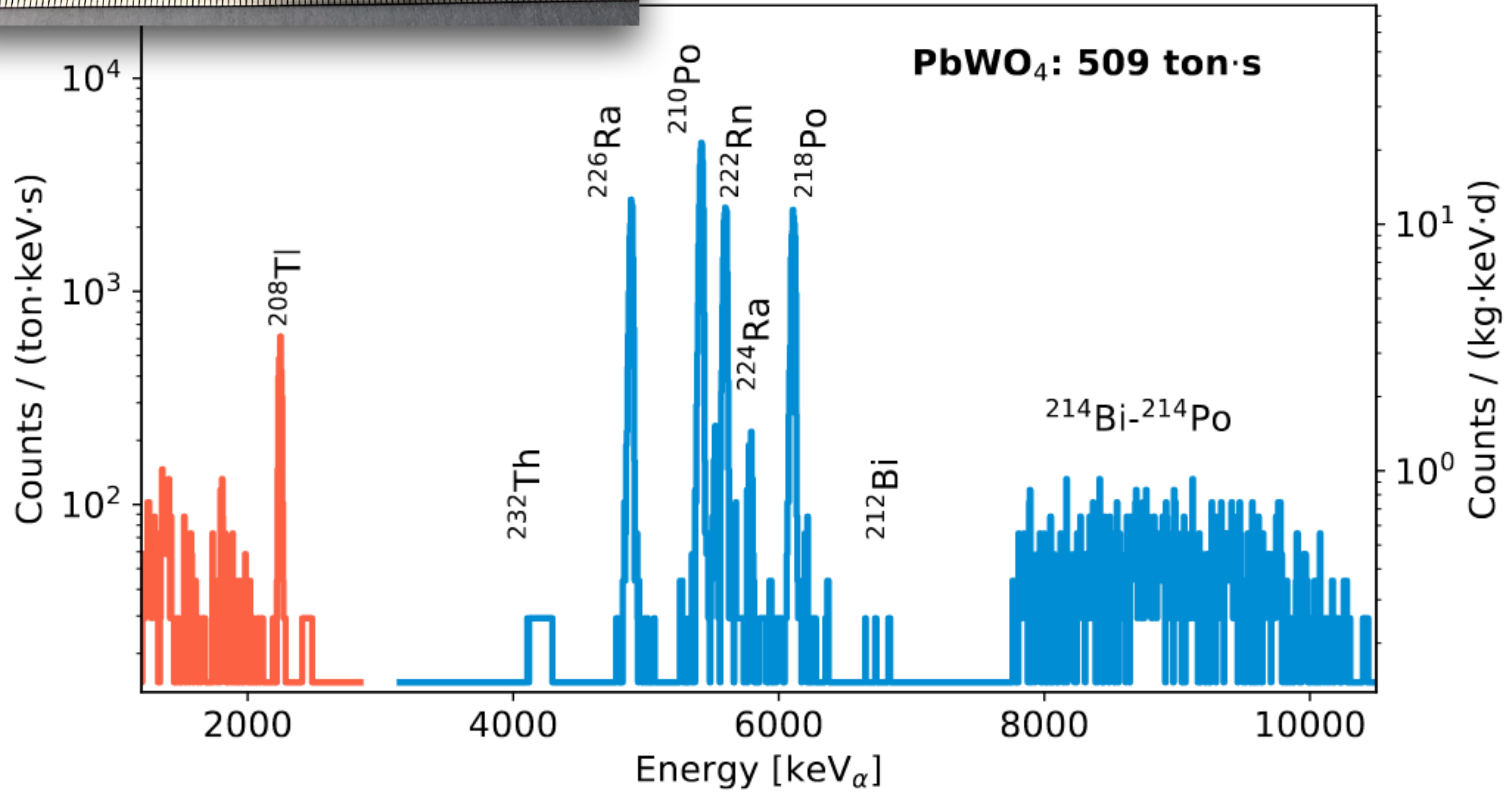
Above ground @ Max Planck Munich (DE)

Nuclear recoil threshold – 300 eV ($PbWO_4$ – 20 g)



RES-NOVA group of interest
Eur. Phys. J. C 82, 692 (2022)

TOTAL ENERGY SPECTRUM



Under ground @ LNGS (IT)

Radiopurity @ μBq/kg scale ($PbWO_4$ – 0.9 kg)

Seminal Paper

40 years ago

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky

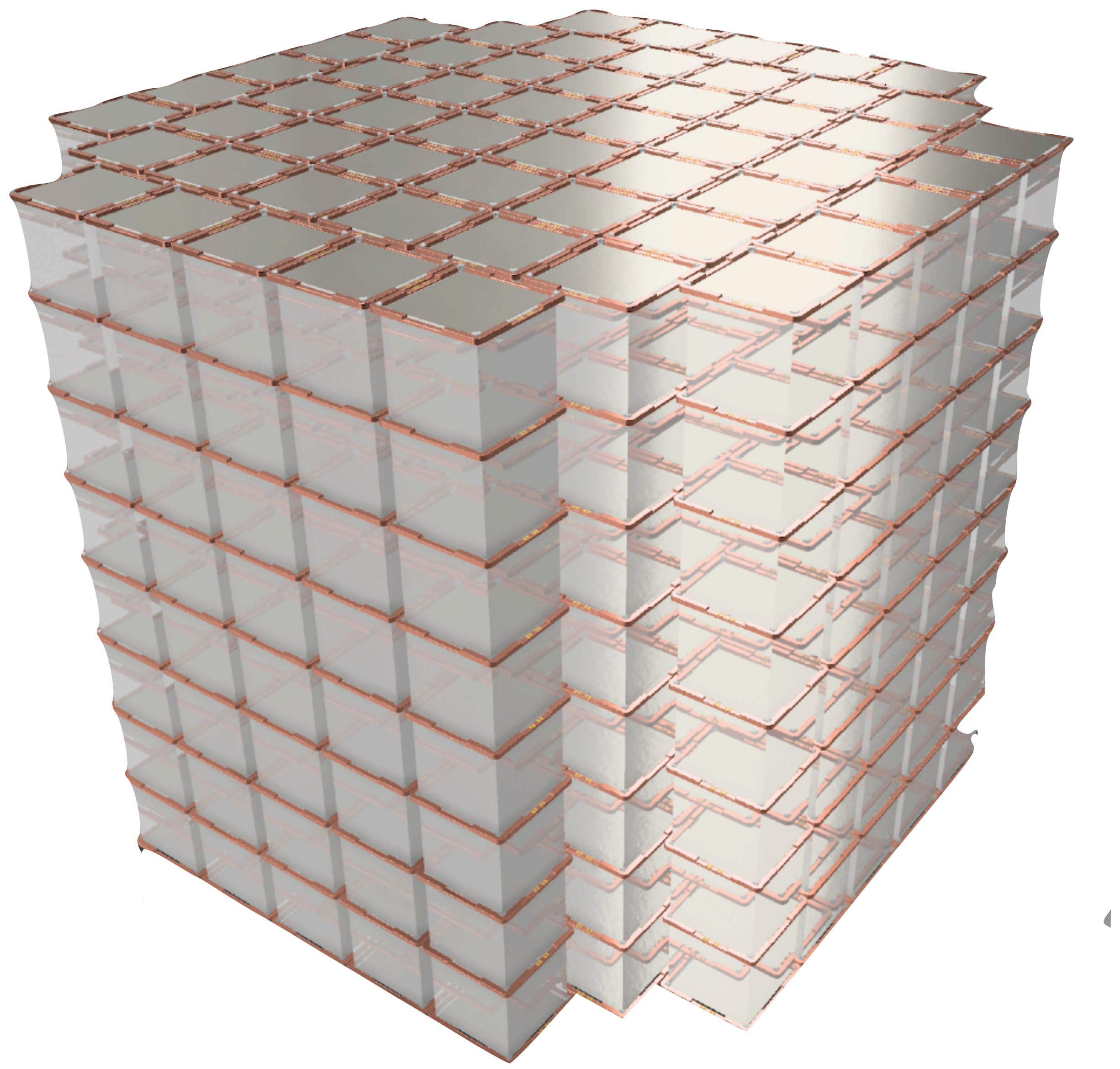
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany

(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small (10–10^3 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

RES-NOVA BACKGROUND MODEL

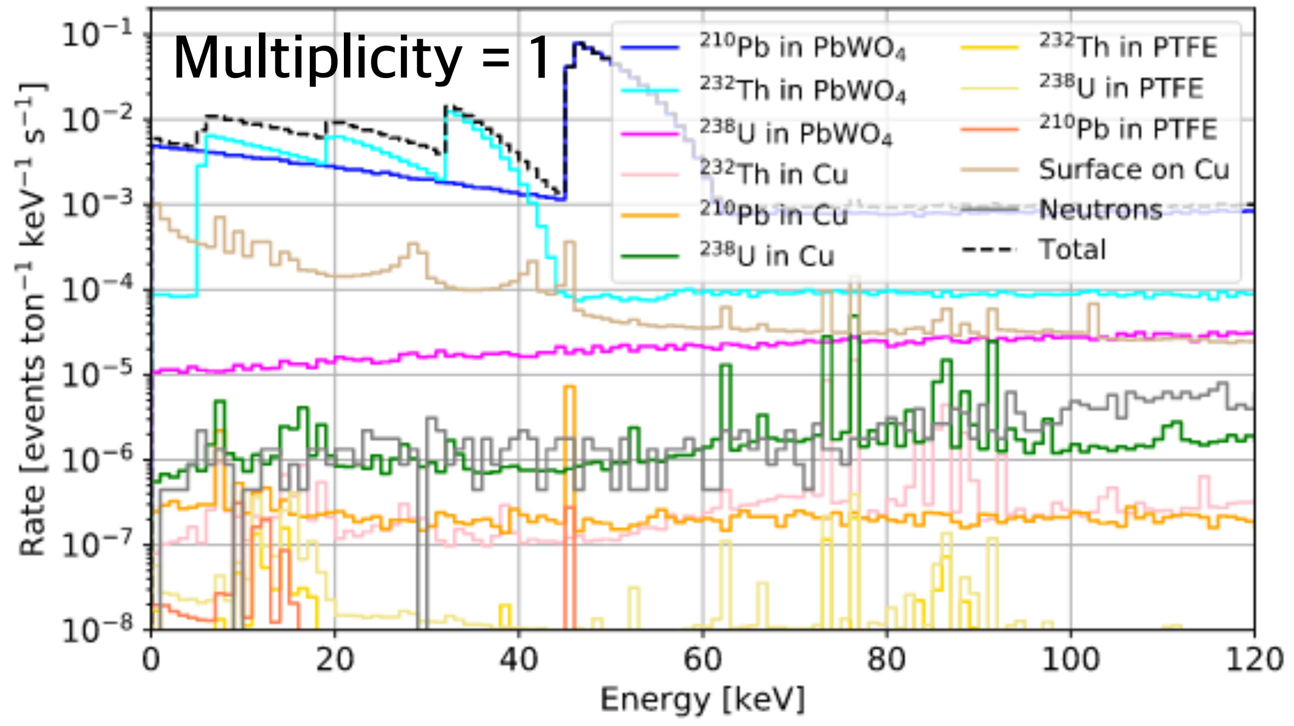
Detector response studies to radioactive background sources – MC simulations

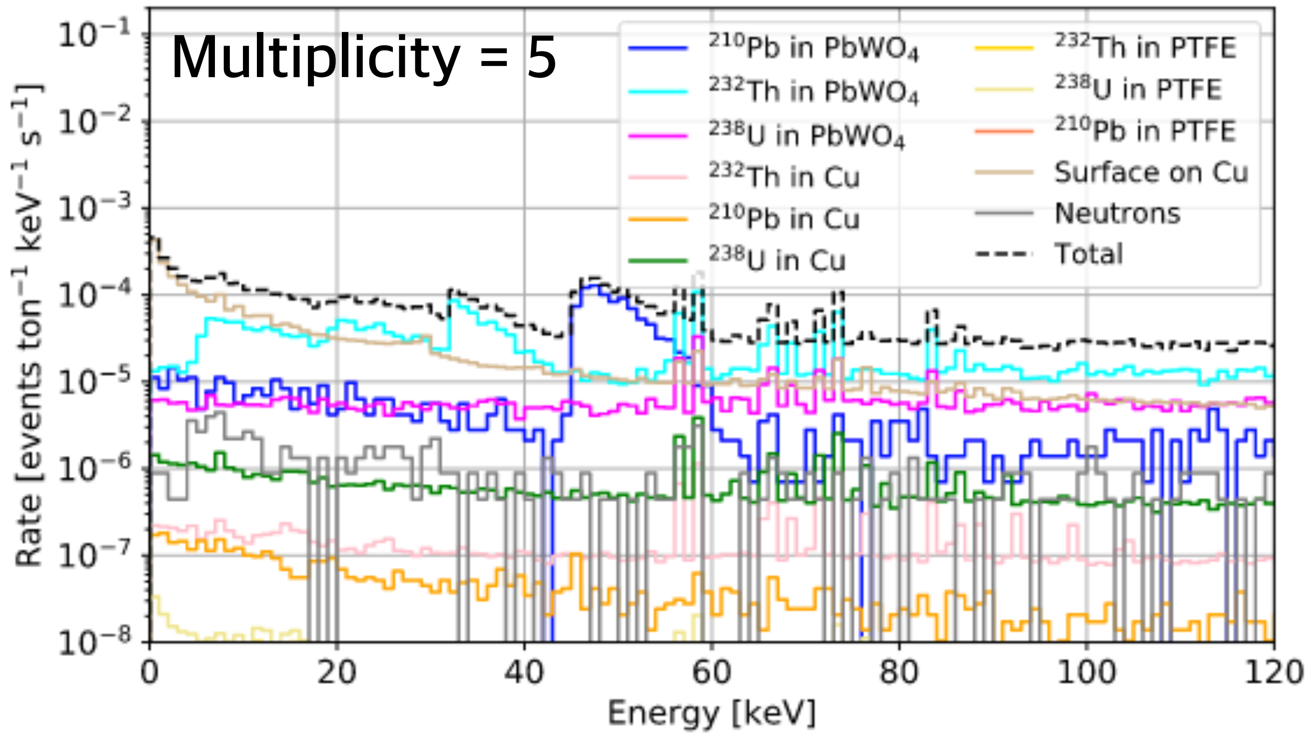


Modular detector

Component	*Source Isotope*	*Activity* [Bq/kg] ([Bq/cm^2])	
$PbWO_4$ crystals	^{232}Th	$< 2.3 \times 10^{-4}$	[50]
	^{238}U	$< 7.0 \times 10^{-5}$	[50]
	^{210}Pb	$< 7.1 \times 10^{-4}$	[36]
Cu structure	^{232}Th	$< 2.1 \times 10^{-6}$	[35]
	^{238}U	$< 1.2 \times 10^{-5}$	[35]
	^{210}Pb	$< 2.2 \times 10^{-5}$	[35]
Cu surface	^{232}Th - 10 μm	$(5.0 \pm 1.7) \times 10^{-9}$	[35]
	^{238}U - 10 μm	$(1.4 \pm 0.2) \times 10^{-8}$	[35]
	^{210}Pb - 10 μm	$< 1.9 \times 10^{-8}$	[35]
	^{210}Pb - 0.1 μm	$(4.3 \pm 0.5) \times 10^{-8}$	[35]
	^{210}Pb - 0.01 μm	$(2.9 \pm 0.4) \times 10^{-8}$	[35]
PTFE holders	^{232}Th	$< 6.1 \times 10^{-6}$	[35]
	^{238}U	$< 2.2 \times 10^{-5}$	[35]
	^{210}Pb	$< 2.2 \times 10^{-5}$	[35]
Environment	neutrons	3.7×10^{-6}cm$^{-2}s^{-1}$	[59]

Radioactive background sources





Detector energy response

L. Pattavina et al., JCAP 10 (2021) 064

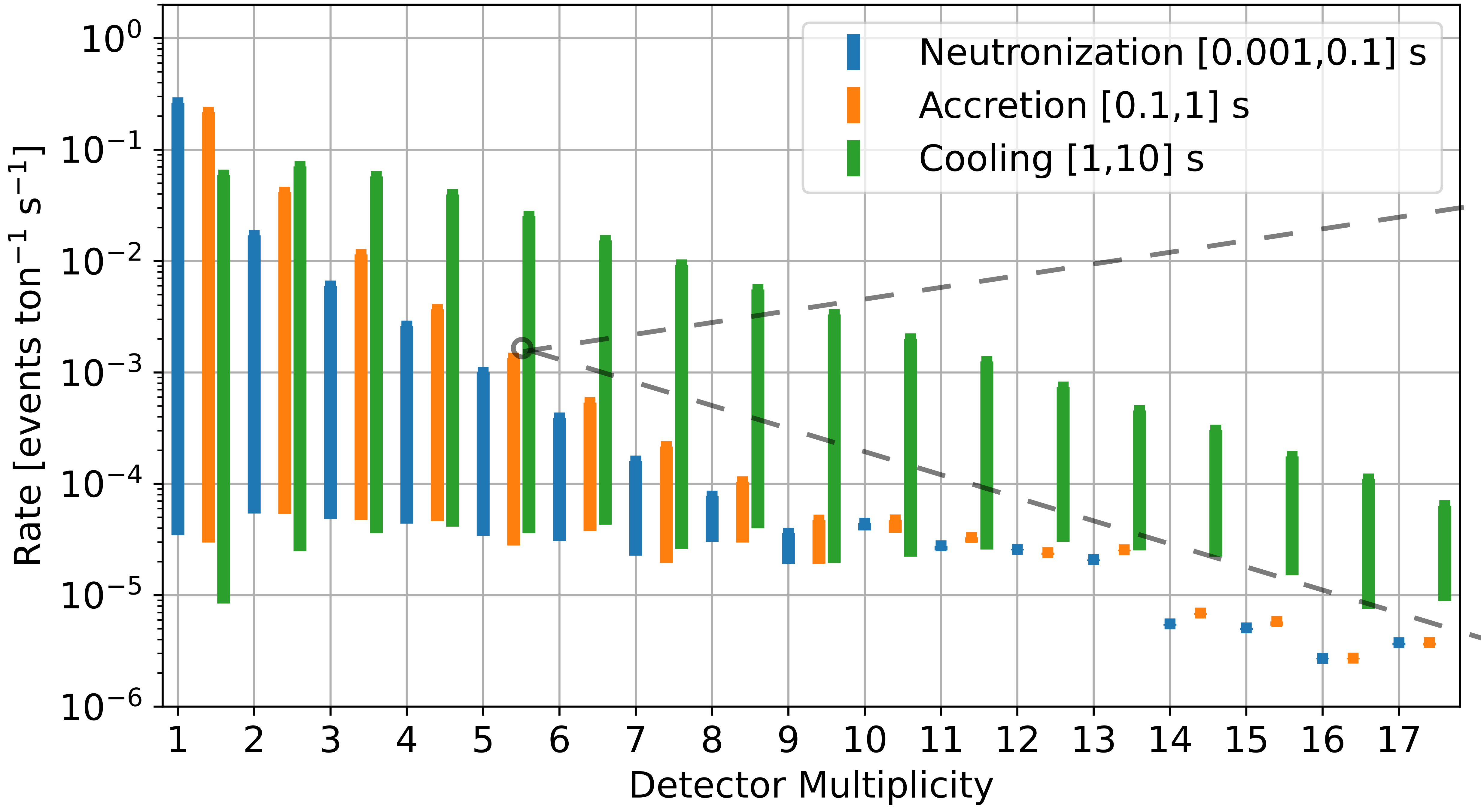
RES-NOVA BACKGROUND MODEL

High multiplicity SN signal → High multiplicity bkg → Low-background

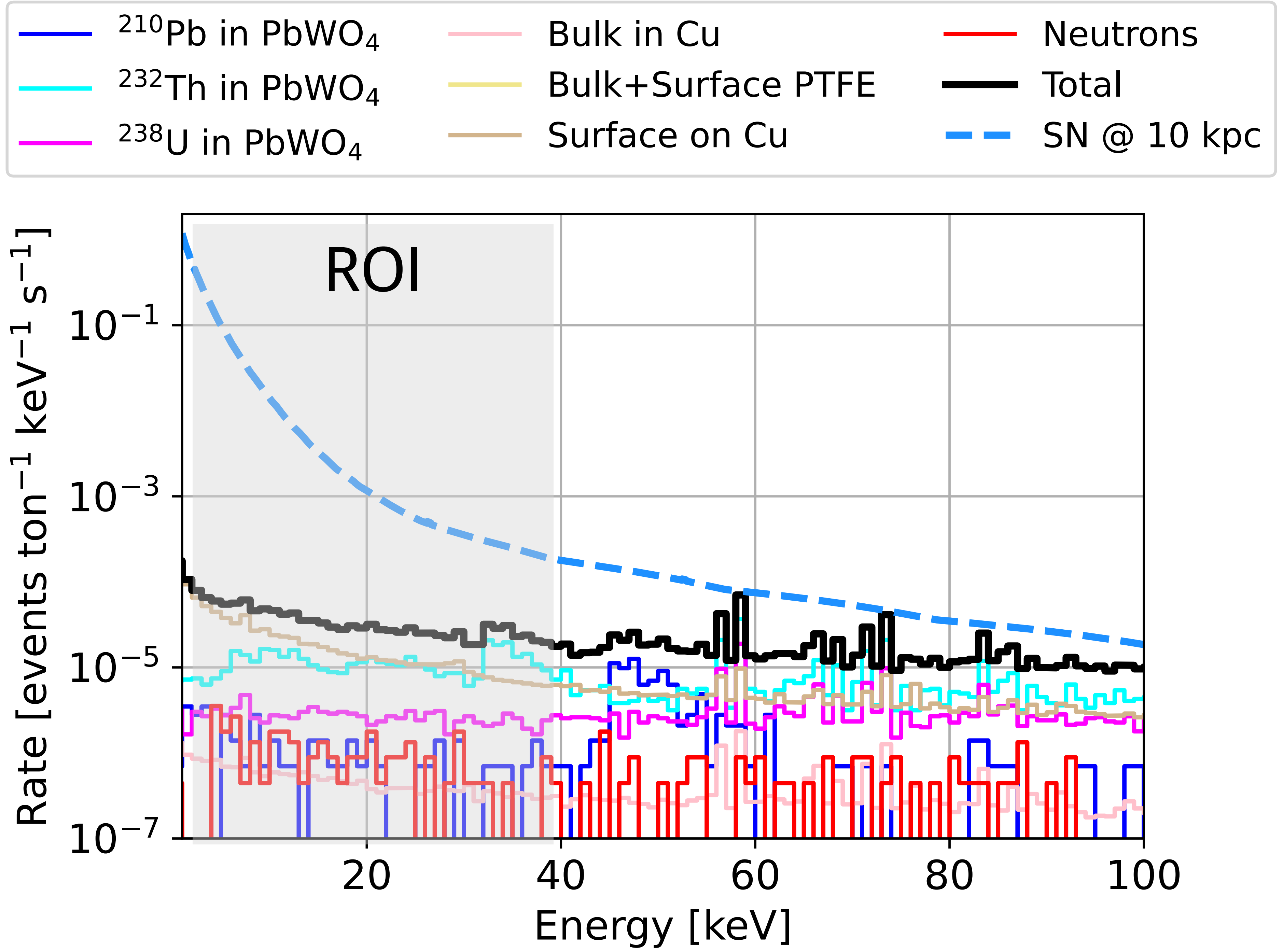
Bkg goal: <10^{-3} ev/ton/keV/s in coincidence mode (no particle ID)

<0.086 c/keV/kg/d

Background rate in the ROI



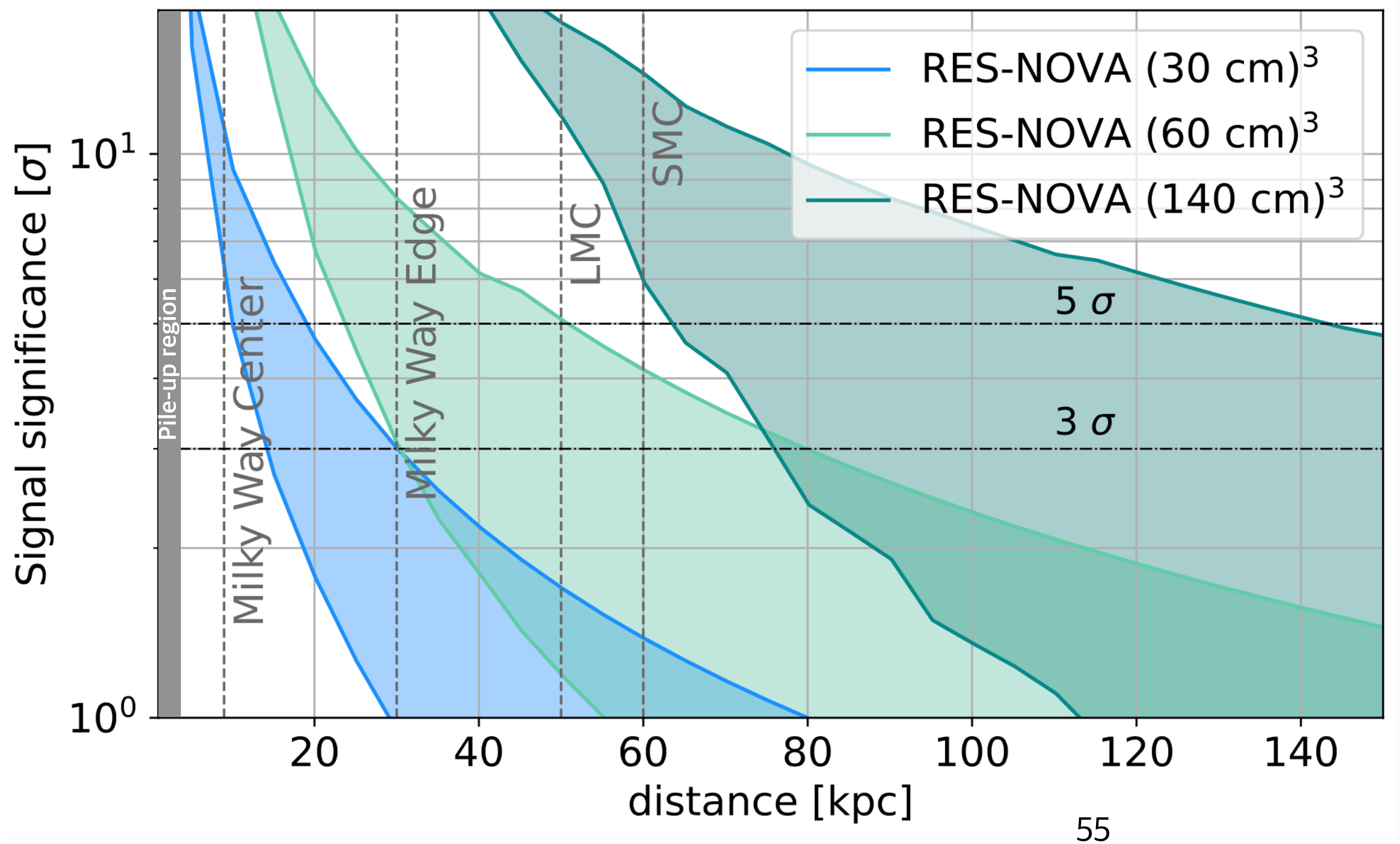
Detector energy spectrum for a SN @ 10 kpc



L. Pattavina et al., JCAP 10 (2021) 064

RES-NOVA sensitivity

small detector great potential



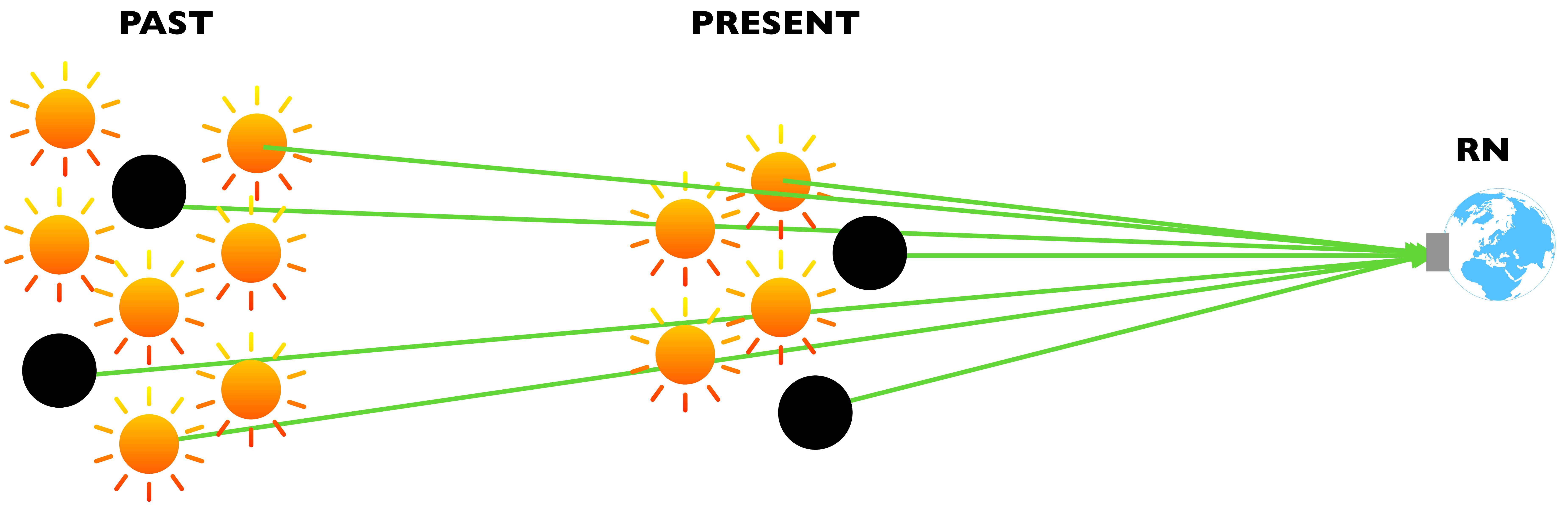
Target: **archaeo-$PbWO_4$**

Energy threshold: **1 keV**

Bkg @ ROI: **10^{-3} c/keV/ton/s/**

L. Pattavina et al., *JCAP* 10 (2021) 064

Diffuse SN neutrino background



$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int_{8M_\odot}^{125M_\odot} dM \int_0^{z_{\max}} dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}$$
$$\times\left[f_{\rm CC-SN}F_{\nu_\beta,\rm CC-SN}(E',M)+f_{\rm BH-SN}F_{\nu_\beta,\rm BH-SN}(E',M)\right]$$

distance

Cosmological rate of CC-SN

Flux at production

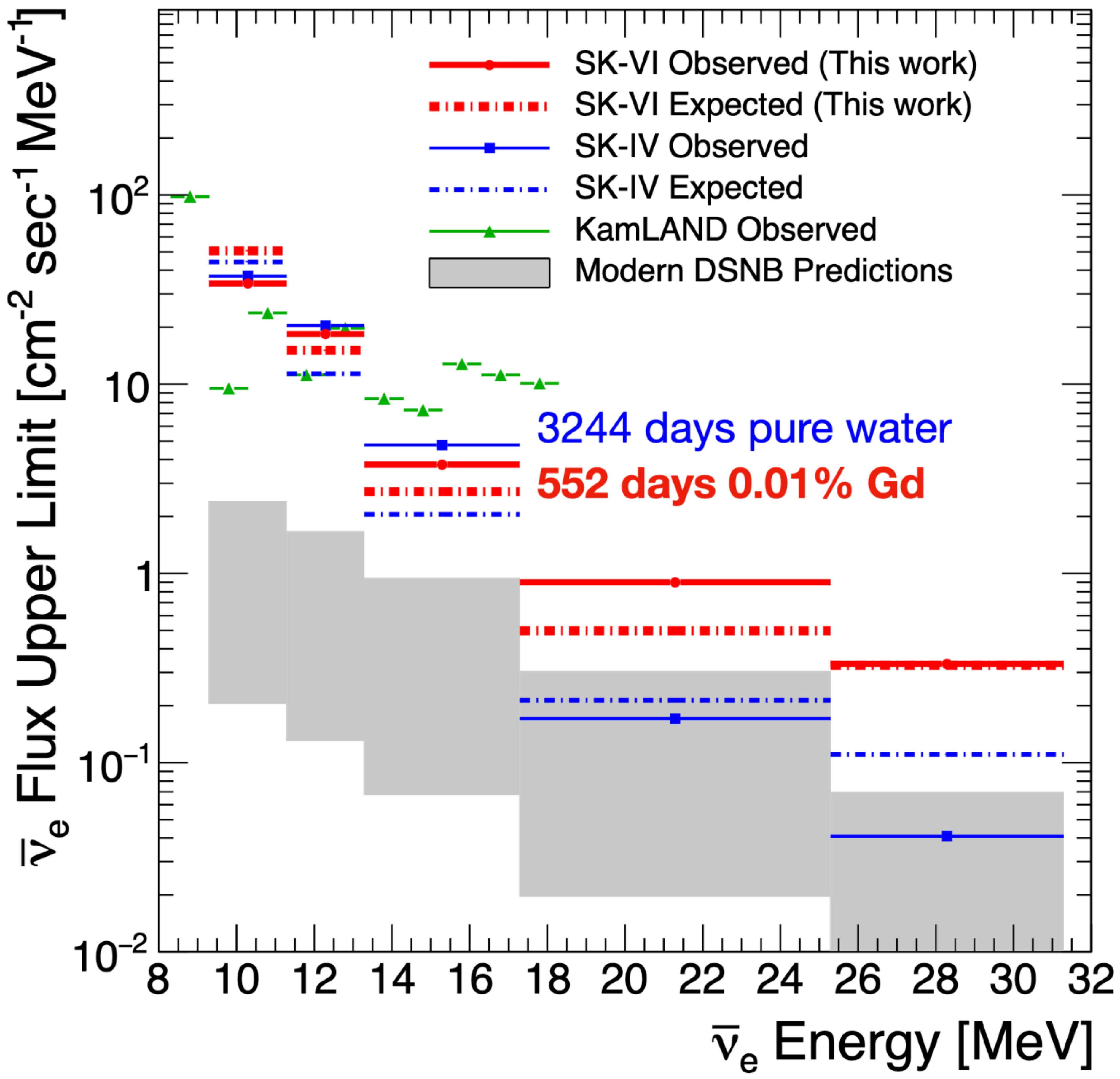
Cosmological rate of fail-SN

Flux at production

Current status of DSNB searches

anti-ν_e DSNB is almost there

DSNB flux energy spectrum



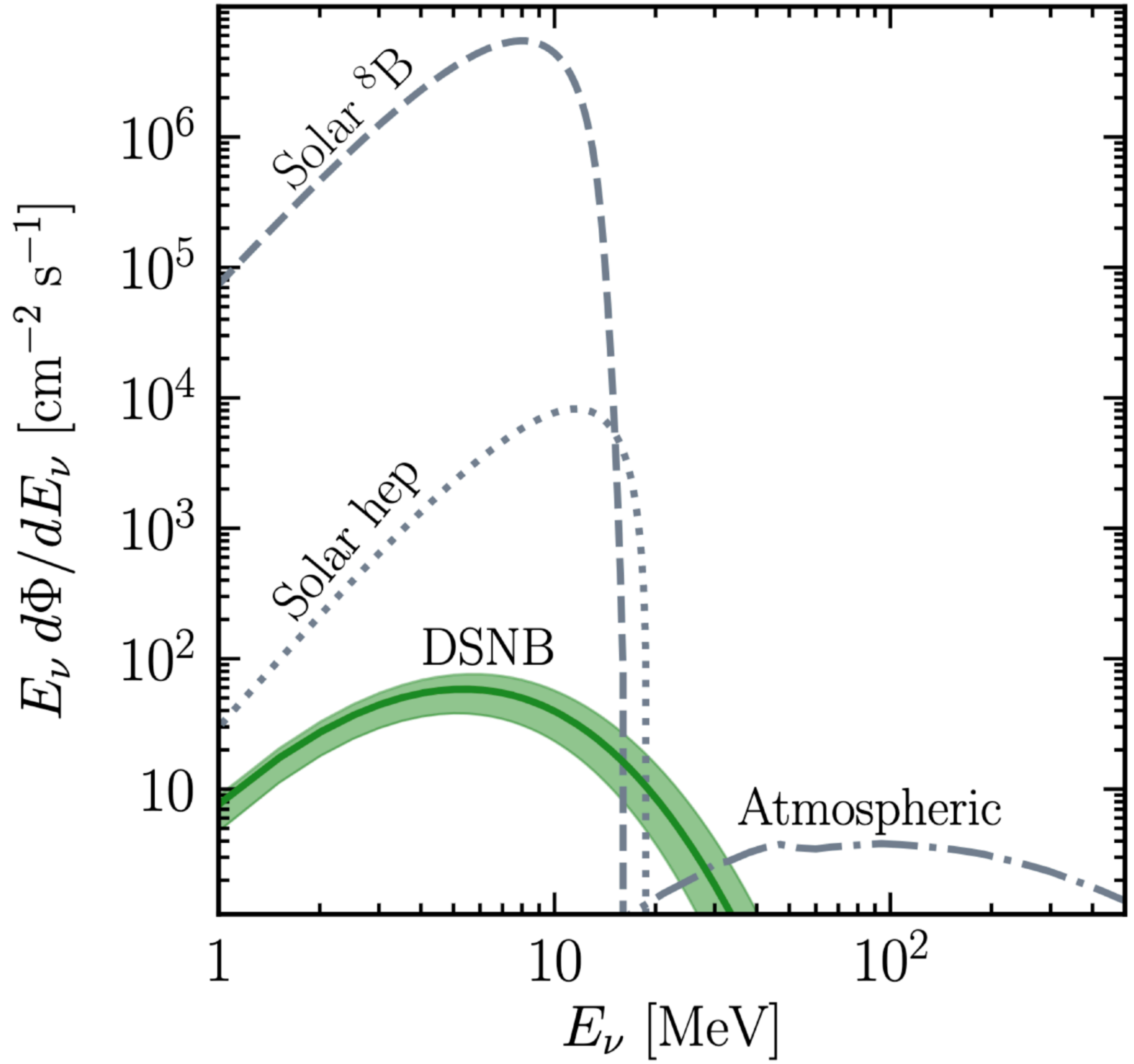
M. Harada et al 2023 ApJL 951 L27

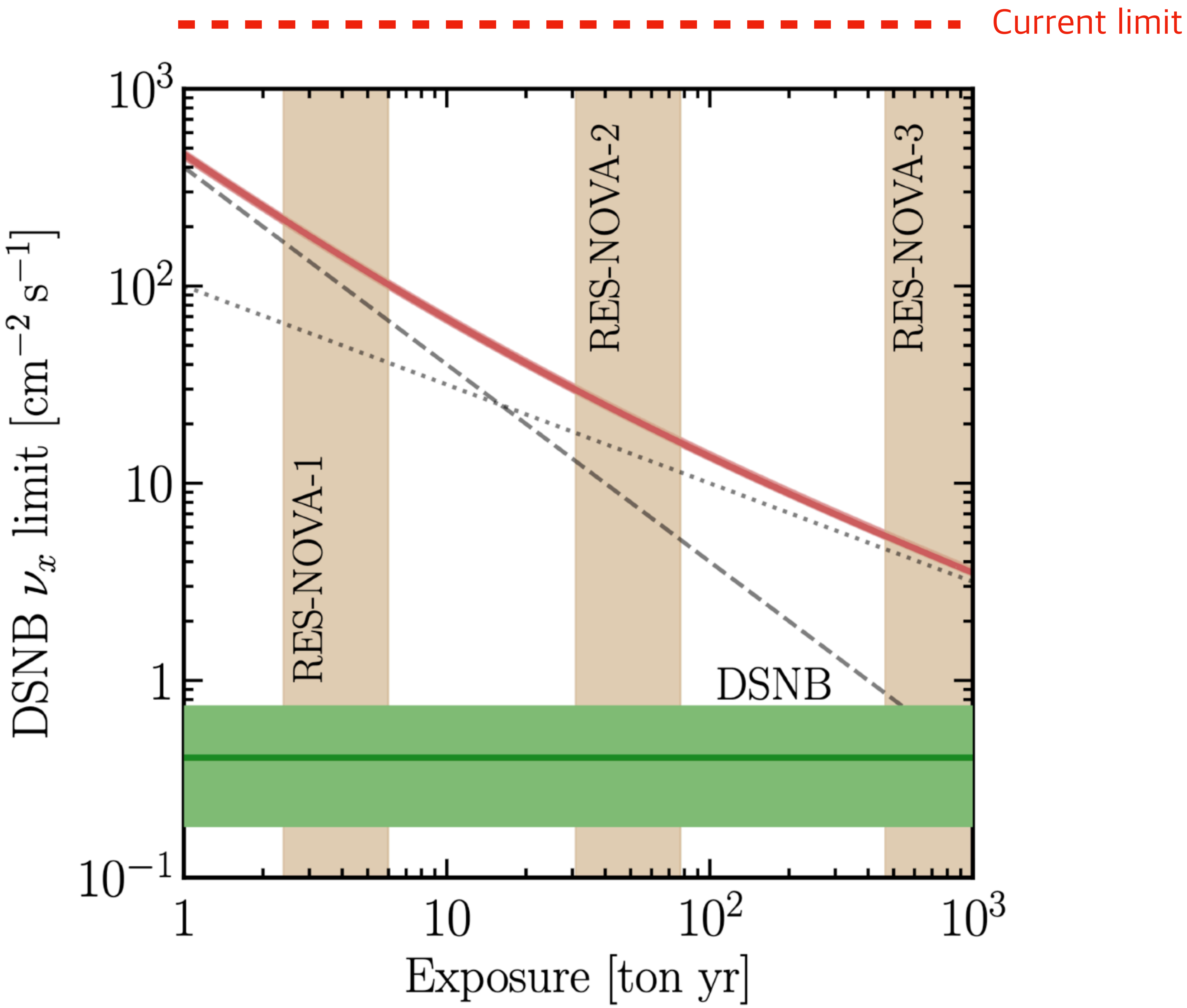
The community has not planned ν_x DSNB searches

DSNB in all flavors with Res-Nova

Unique opportunity

Neutrino energy spectrum



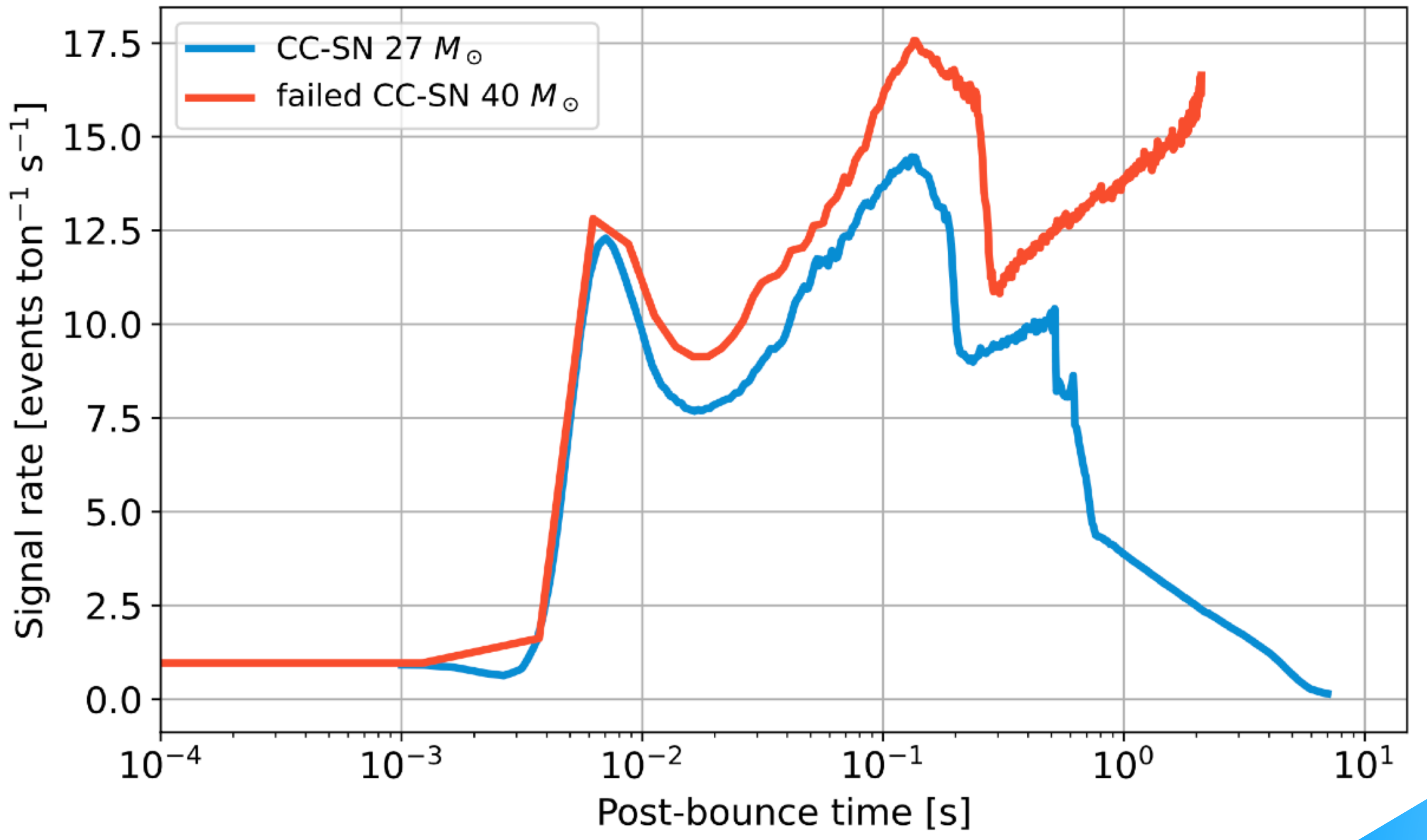


A. Suliga, J. Beacom, I. Tamborra, Phys. Rev. D 105, 043008 (2022)

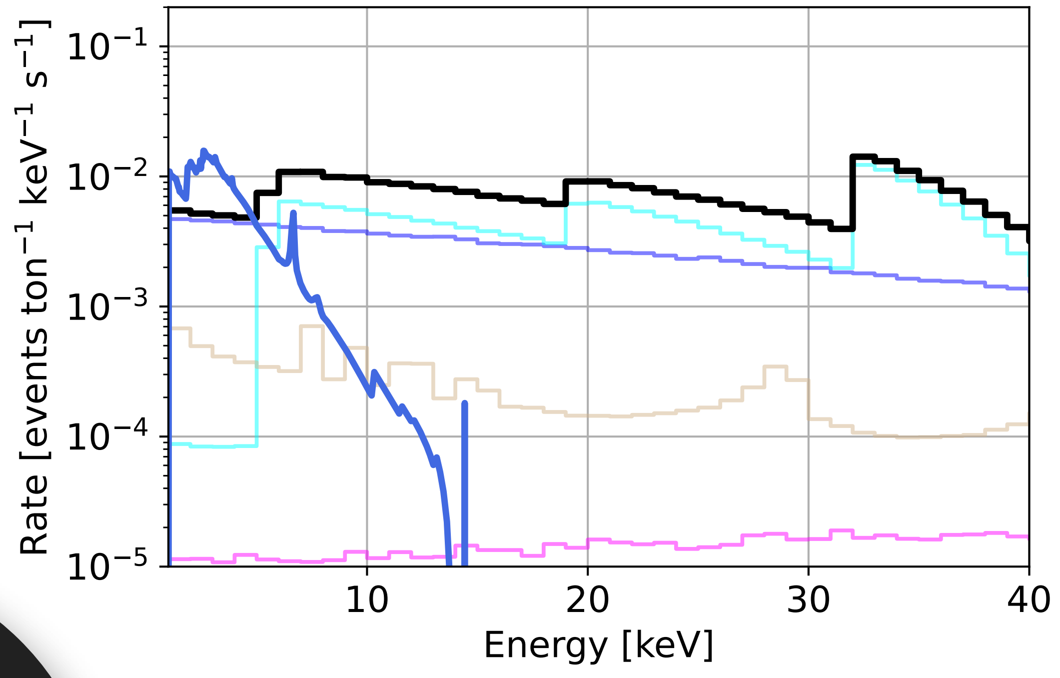
RES-NOVA Impact

MULTI-DISCIPLINARITY

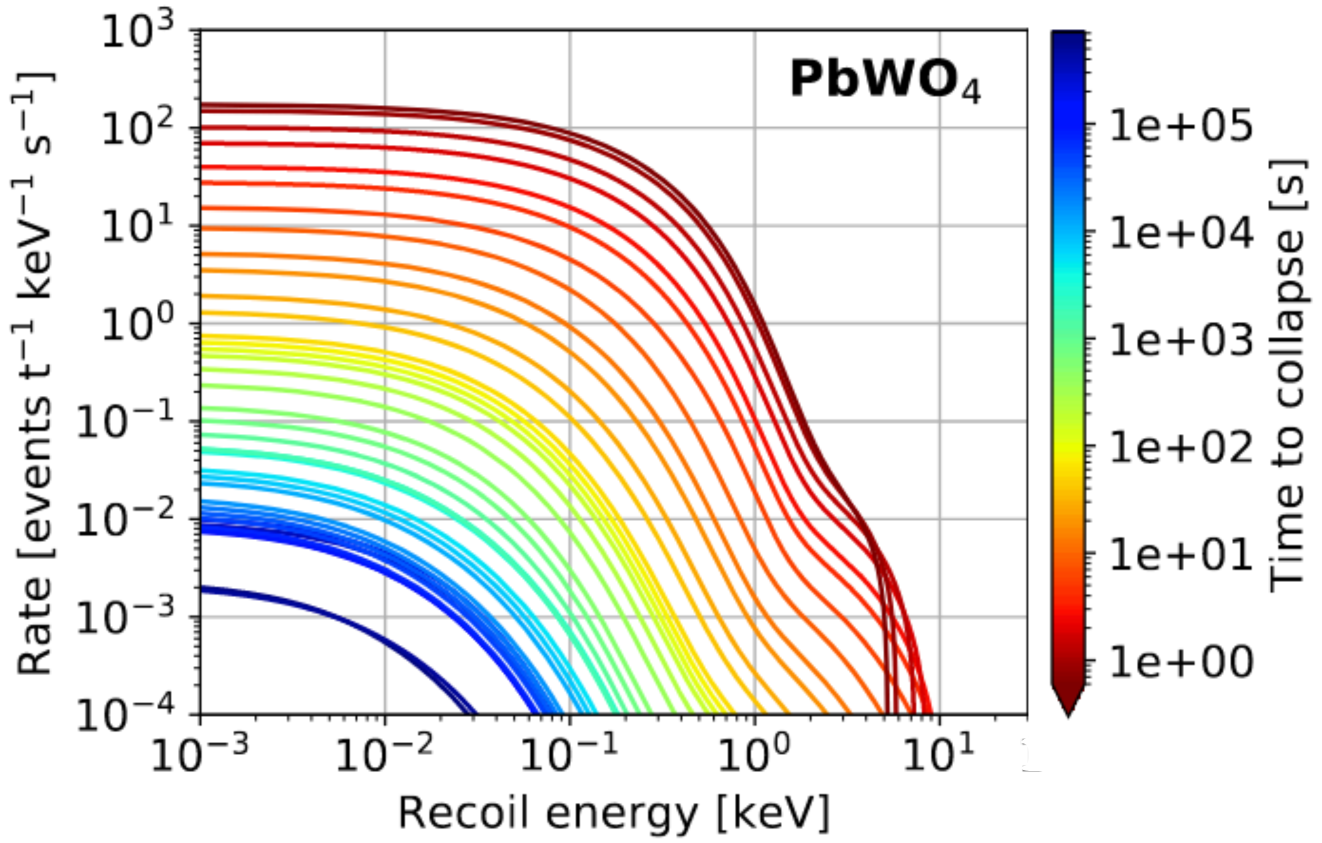
Core Collapse model discrimination



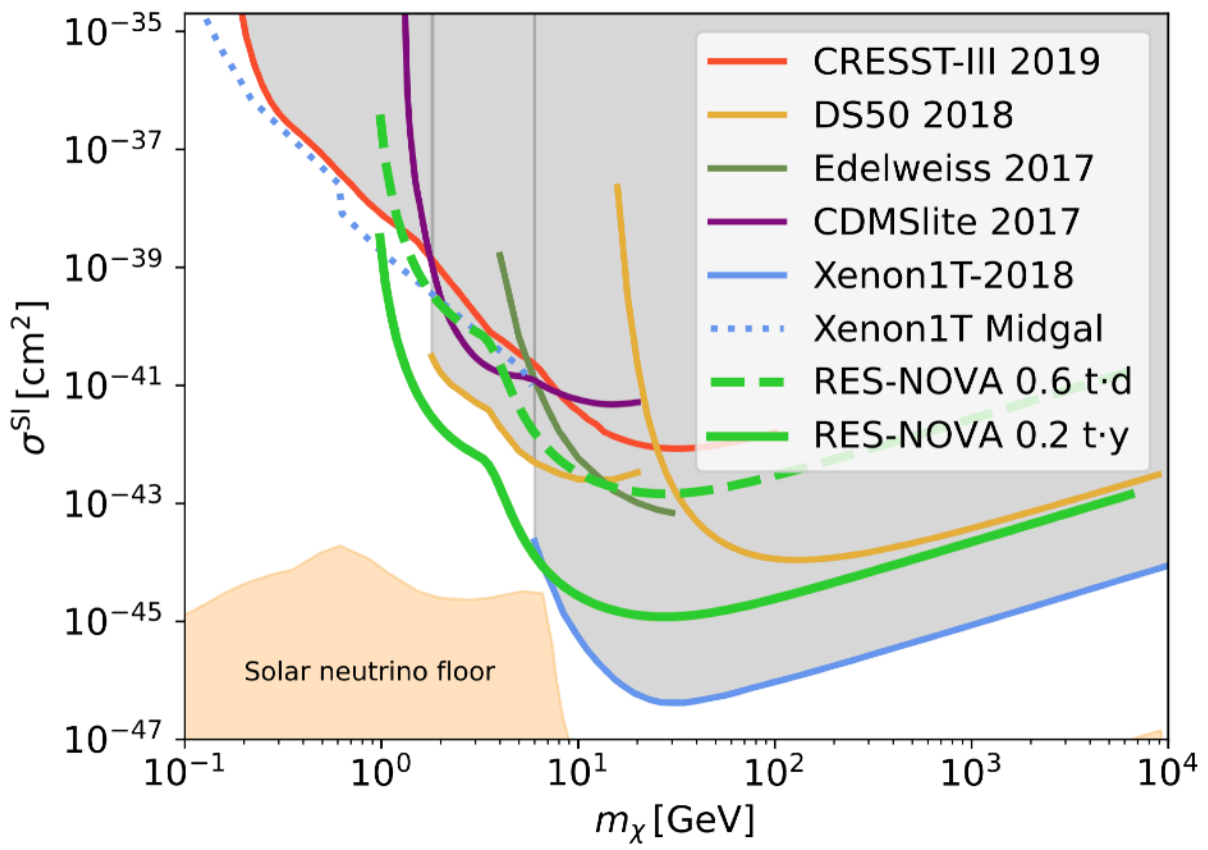
Solar Axion searches



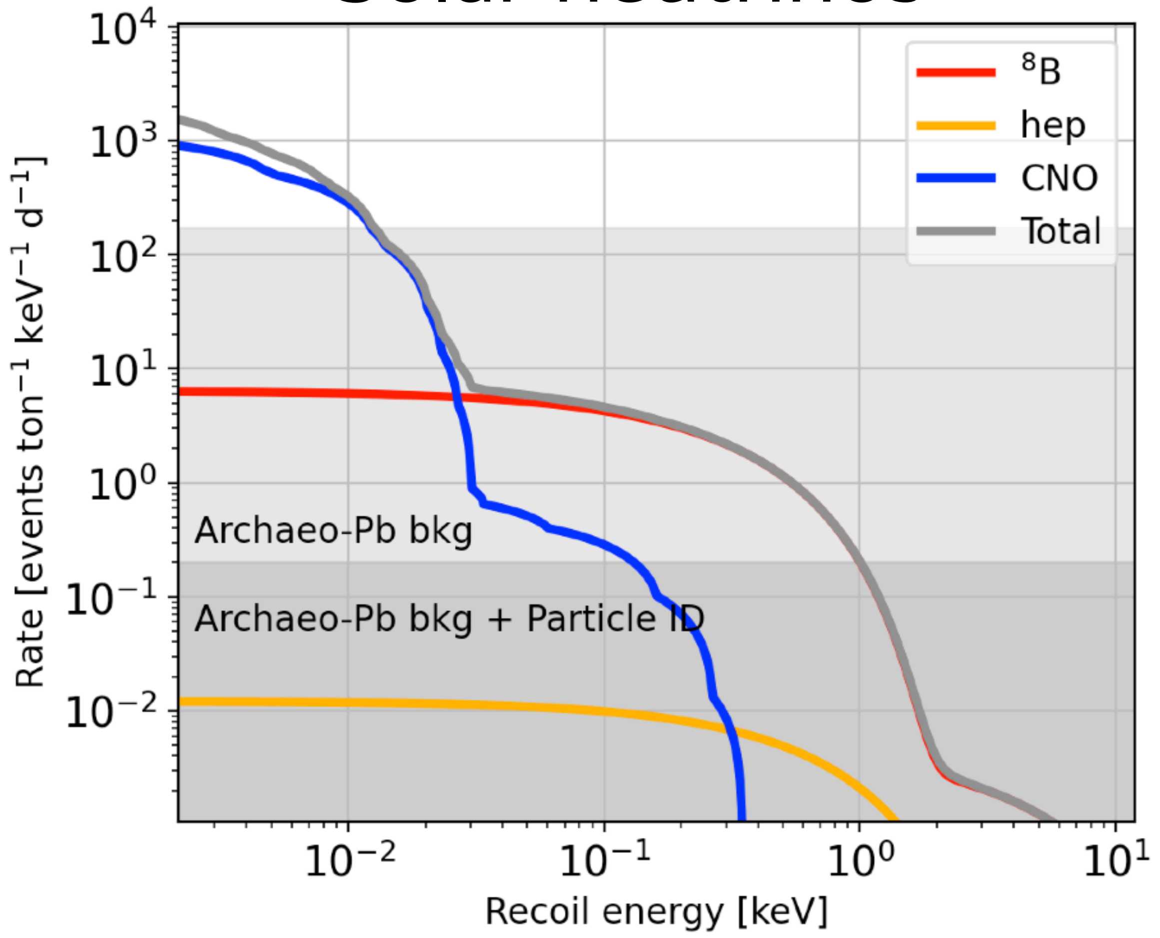
Pre-SN neutrino detection



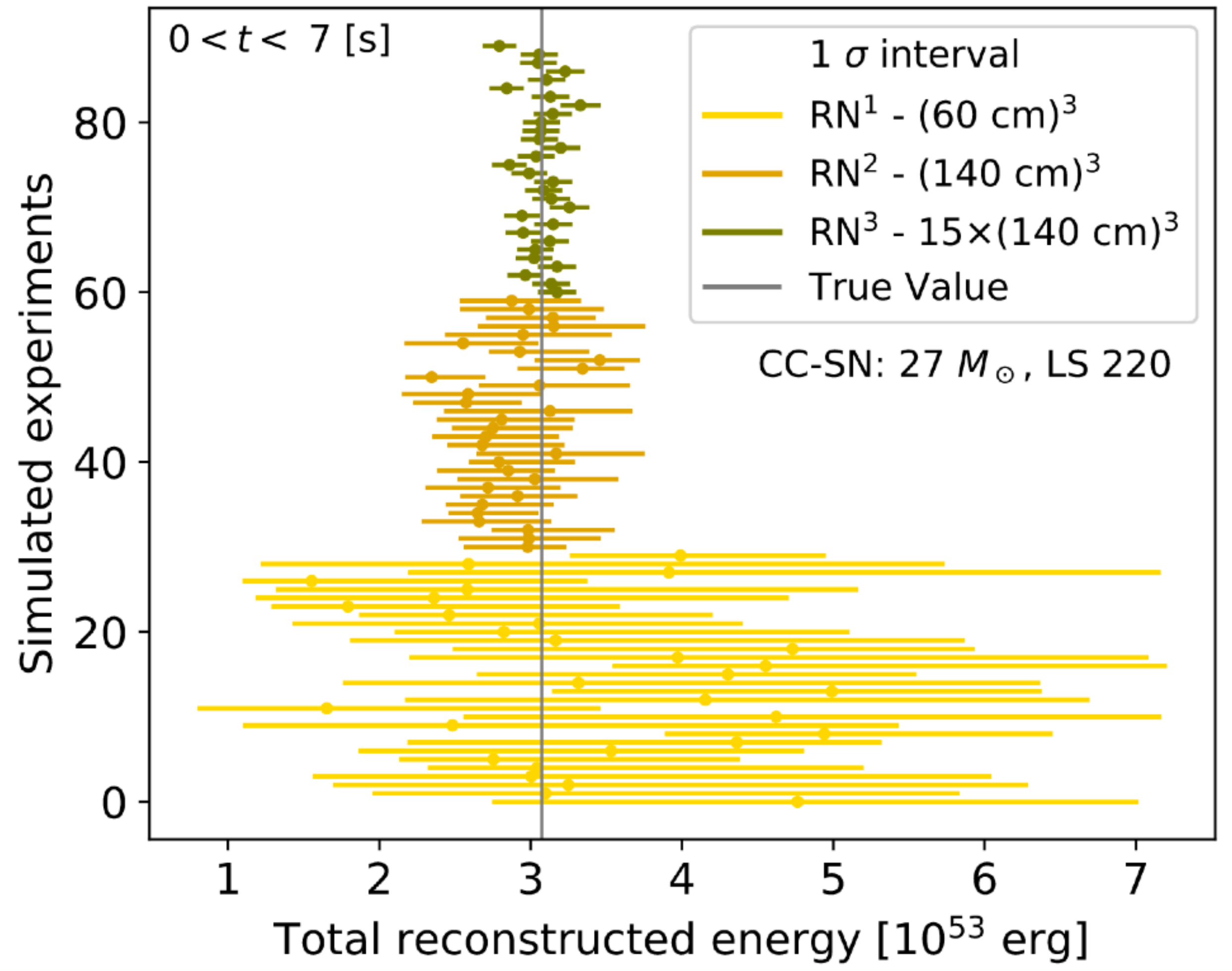
Direct DM searches



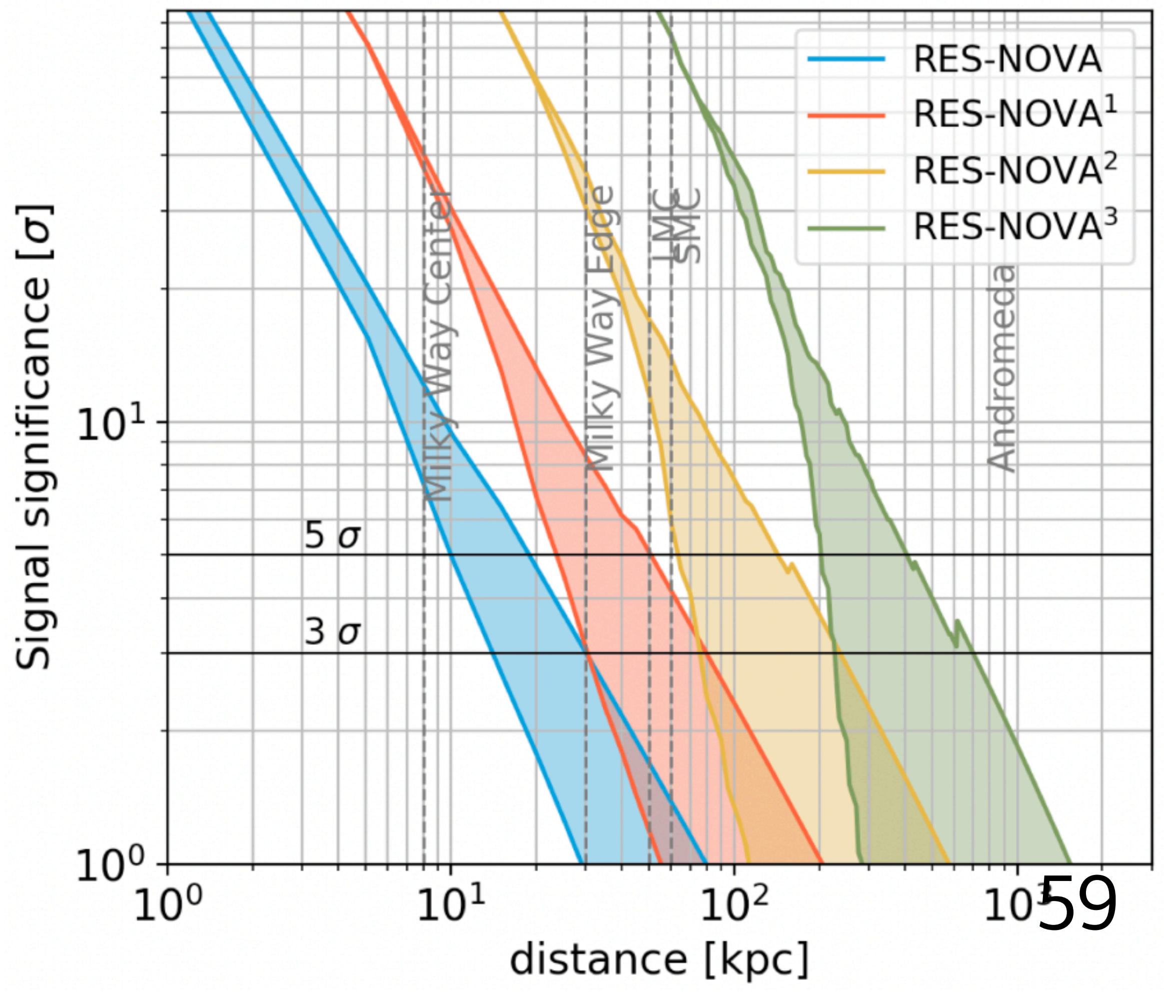
Solar neutrinos



Precise ε_{tot} reconstruction



Deep space exploration



P. Eller, LP et al JCAP 10 (2022) 024
LP et al., JCAP 10 (2021) 064
LP et al., Phys. Rev. D 102, 063001 (2020)

RES-NOVA Impact

MULTI-DISCIPLINARITY

Core Collapse model discrimination

Solar Axion searches

Pre-SN neutrino detection

Precise ε_{tot}

Big resonance in the community:

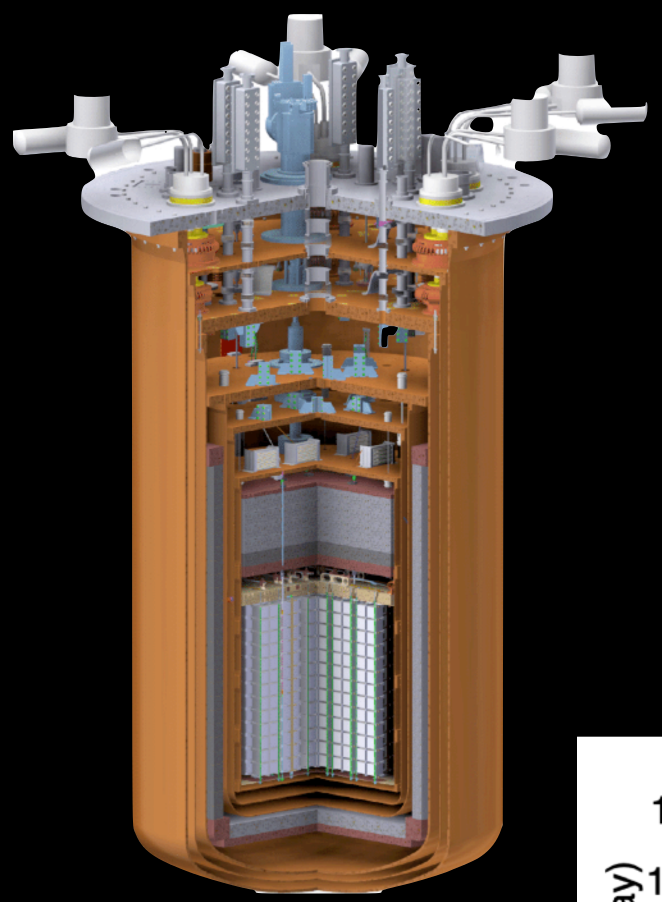
- Neutron skin measurement Phys.Rev.D 106 (2022) 12, 123034
- Neutrino lifetime measurement JCAP 05 (2024) 002
- Primordial black-holes Phys.Lett.B 829 (2022) 137050
- Non-standard neutrino interactions Nucl.Phys.B 977 (2022) 115737
- Booster Cosmic neutrino background Phys.Rev.D 106 (2022) 9, 095042
- ...

P. Eller, LP et al JCAP 10 (2022) 024
LP et al., JCAP 10 (2021) 064
LP et al., Phys. Rev. D 102, 063001 (2020)

Conclusions: what is matter?

Versatile experimental technique - tuneable to the physics target

> 0vBB, DM, neutrino observatory, solar axion, nuclear physics, ...

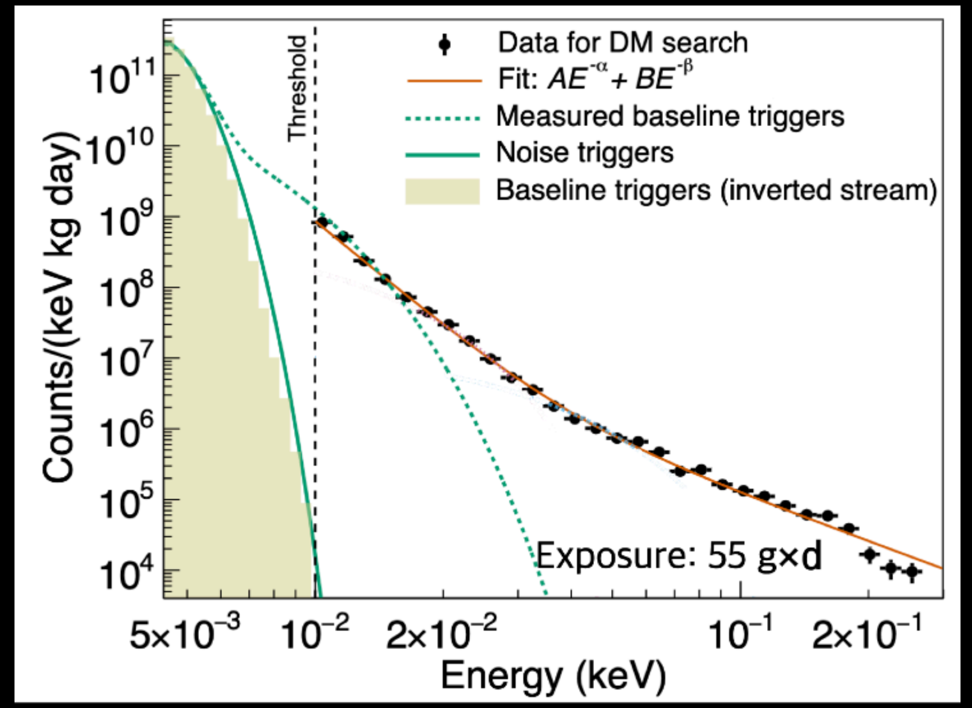


Laboratory test of matter-antimatter asymmetry

> high-impact physics program with CUPID

Dark Matter fundamental properties

> cryogenic detectors (CRESST) are leading light-DM searches



Neutrino interaction with matter

> long-term physics program with RES-NOVA

> astrophysical observatory - broad physics reach

RES-NOVA